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Phytoremediation for rehabilitating bauxite-mined sites

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A B S T R A C T

Recent industrial revolutions cause bauxite mining activities across the globe to become notably more active. However, ceasing bauxite mining activities left bauxite mining sites barren without any vegetation, causing environmental and health problems, such as dust and red muds. Existing remediation techniques such as physical separation, incineration and chemical precipitation may increase risks of additional contamination or be more costly; thus, there is a need for greener and more feasible method such as phytoremediation. Phytoremediation and revegetation may help to make the barren lands to become green again with lower costs. Researches on phytoremediation technique to solve environmental problems in Malaysia are still limited but show great potentials. Works and researches on phytoremediation for rehabilitating bauxite-mined sites has been successfully conducted across the world, showing promising futures for barren bauxite mining sites in Malaysia. This study summarizes the general scenario of bauxite mining activities and the potential of phytoremediation, focusing on reclamation of bauxite-mined lands.

Keywords: Phytoremediation; Rehabilitation; Revegetation; Land reclamation; Bauxite-mined sites; *Jatropha curcas*

1. Introduction

Malaysia has experienced strong economic growth over the past decade, with rapid development in various sectors such as urbanization, industrialization and mining. It was reported that Malaysia is on the steady economic growth path, thus expected to be the 24th largest economy by 2050 [1]. While the profit from the economic activities is skyrocketing, there are also uproars by the community on issues related particularly on health and environment. This is due to the rapid industrialization, that leads to an increase in the number of carbon emissions and hazardous wastes generated, causing damaging effects to the environment [2].

Heavy metal contaminations of soils and crops also triggered the concerns on possible effects on human [3]. Heavy metal refers to toxic elements which are released into the environment through natural and anthropogenic sources. This group becomes very prominent during this rapid industrialization era as more heavy metals are involved in the industries such as mining and production [4]. Our mother earth is rich with minerals and ores, which have been extracted and benefited humans in various ways. Increased mining activities also cause a rapid increase of heavy metal contaminations as various elements are involved in mining and processing of the ores. This leads to the need for a way to restore the environment.

Several remediation technologies have been developed to solve problems relating to soil and water contaminations. Physical remediation method includes physical separation, thermal processes such as vitrification and incineration,

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and land excavation; which mostly are ex-situ methods that require high energy cost and have destructive nature. Meanwhile, the chemical methods such as soil washing and encapsulation results in highly contaminated effluents that needs to be treated [5]. One of the useful and feasible alternatives is phytoremediation, the use of green plants to remediate and restore contaminated sites.

2. Bauxite mining

2.1. Global and Malaysian scenario

The term 'bauxite' originates from Les Baux in south-east France, where it was first described by Berthier in 1821 [6]. Bauxite is defined as soil or rock formation which is composed mainly of aluminium hydroxide minerals. It also refers to lithified or unlithified, residual weathering product rich in alumina and low in alkalis, alkaline earth and silica. Bauxites are usually in colour of iron, ranging from red to brown or yellow. Bauxite mining supplies raw materials that are needed for primary aluminium production. It is said that more than 80% of bauxites produced in the world are extracted from shallow open-pit mines, meaning that it can be extracted without using explosives [7].

Bauxite is being mined, refined, exported and imported actively in many countries globally. According to the data reported by U.S. Geological Survey [8], mineral commodity summaries on February 2019, bauxite resources are estimated to be as abundant as 75 million tonnes, with the most being in Africa (32%), followed by Oceania (23%), South America and the Caribbean (21%) and Asia (18%). Some countries like Malaysia, enforced bans on bauxite mining due to some issues such as environmental pollution, community uproars and political interests; but still permits exports of stockpiled bauxite [8,9].

As stated in Malaysian mineral yearbook 2010 [10], bauxite mining has been discovered and mined in Johor since the colonial era. Since then, bauxite has been exported, with a total value up to millions of ringgits every year. Tanah Makmur Bhd, which operates in Pahang, solely exported 684,389 metric tonnes of washed bauxite in 2014, contributing approximately 60%–70% of Malaysia's export that year, thus securing RM 86 million for the financial year 2014 [11]. The price of Malaysia bauxite is about RM 191 per tonne in 2015, which equals to USD 45.97 [12].

The explicit bauxite mining in Pahang has caused serious health problems to the locals. Bauxite mining in Kuantan causes air pollution, dusty residential area, road damage, agricultural problem, land erosion, water and food resource problem, and loss of calmness to the locals [13]. Air pollution, in particular, causes asthma, allergy and cough. The unrestrained mining activity and poor post-mining management that leaves barren bauxite mining sites unvegetated also cause severe mud flood due to surface runoff and soil erosion which eventually contributes to water pollution, contamination of water sources and loss of natural fishing places [9]. Routine soil stripping reduces the storages and activity of soil organic matter, putting long-term sustainability in question [15]. Excavations of top layer soils loosen the soil structures, thus increasing the risks of road damages and soil erosions. These problems alarm the community, thus raising the concerns to remediate the environmental problems.

3. Phytoremediation

Phytoremediation is one of the feasible ways to mitigate environmental problems. Phytoremediation is defined as the usage of plants to clean up the environment [15]. The term phytoremediation originates from "phyto-", which is a Greek prefix meaning plant and the Latin suffix "remedium" which means to cure or restore [16].

There are several phytoremediation strategies including phytoextraction, rhizofiltration, phytostabilization, phytodegradation, and phytovolatilization (Fig. 1). Phytoextraction is a phenomenon where plant accumulate and store metals from soil into their harvestable parts [17]. The accumulated toxic elements can either be eliminated by disposing of harvested plant parts or by extraction to recover potential valuable compounds [18]. Meanwhile, in rhizofiltration, the roots of plants absorb, precipitate and concentrate heavy metals from the contaminated effluent [19]. Phytostabilization uses plants to reduce the bioavailability of the pollutants in the environment, phytodegradation uses plants and associated microorganisms to degrade organic pollutants, and phytovolatilization uses plants to volatilize pollutants [20].

Phytoremediation has many advantages such as large-scale application, low cost, ecologically safe, have potential economic returns and reduce the amount of hazardous waste [21]. The plants also indirectly increase soil aeration, reduce soil erosion and enhance the rhizospheric micro-fauna and flora. Furthermore, phytoremediation is an easily applicable method and its application towards a wide range of metals, radionuclides, and organic substances are available [18].

The total cost of phytoremediation for a case study involving arsenic (As), cadmium (Cd) and lead (Pb) in Huan Jiang Maonan Autonomous County located in China was USD37.7/m^3, of which infrastructure cost being the highest [22]. High infrastructure cost was mainly because of slow economic development and serious contamination. The average cost of other remediation technologies is shown in Table 1, with a cost ranging from USD 4.7 to 813 per m^3. Comparatively, phytoremediation cost is lower than other remediation technologies.

Phytoremediation can offset all the cost needed to remediate the land if the vegetations used can help the landowners to generate income. Studies conducted on land reclamation in Australia proved that reclaimed lands can be used for multiple purposes, such as nature conservation, source of timber production, mineral extraction, and recreation [26]. Bioenergy crops such as *Jatropha curcas* can also be used for land reclamation as it can be used for biodiesel production while helping to reclaim the polluted and barren lands [27].

Nevertheless, phytoremediation has several limitations. Phytoremediation is quite a long process that may take tens to several hundred cropping cycles, which may require several years or seasons to completely clean up a contaminated site [28–30]. As the roots of plants can only penetrate several meters in soils, this technology only suited for treating contaminants on the surface layers of soils [31]. Usage of non-native plants may also affect the biodiversity of the area and the harvested toxic plant biomass must be handled properly

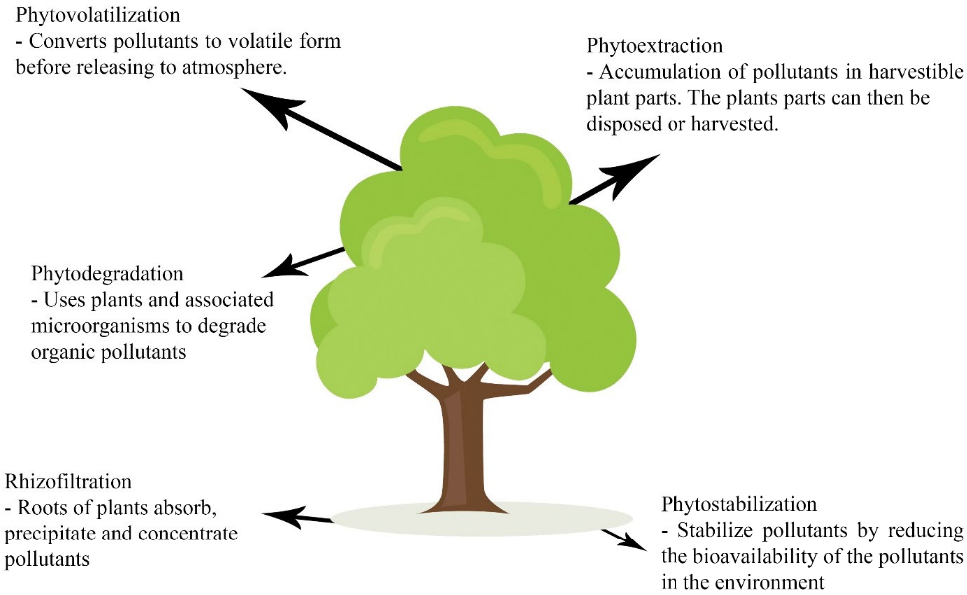

Fig. 1. Various types of phytoremediation strategy.

Table 1
Average cost of other remediation technologies

Reference	Technique	Costs (USD/m^3)
[23]	Turnover and attenuation method	4.7–5.6
	Solidification method	87–190
	Extraction method	240–290
[24]	Off-site disposal method	480–813
	Off-site high-temperature thermal desorption method	81–252
	On-site bio-pile method	130–260
	On-site landfarming method	Less than 100
[25]	Soil washing method	71.4
	Bioremediation method (microbial degradation)	59.9
	Excavation method	47.8

as it may be classified as hazardous waste [32]. Since hyperaccumulators may only accumulate one or two metals at most, multiple plant species may be needed to remediate a polymetallic site such as mine sites [33].

One of the key factors affecting the success of phytoremediation is plant selection. For example, plants used for phytoextraction should be able to tolerate high concentration of heavy metals, can accumulate a significant level of contaminants into plant parts, have fast growth rate, can generate reasonably high biomass and have profuse root system [31]. For example, *Arundo donax* (giant reed) grown on bauxite-driven red mud can transfer the metals absorbed into the shoot and concentrating them in the stalk and leaves [34], which is a feature of plants used for phytoextraction. The giant reed also improved soil quality and being a non-edible plant, it is suitable as phytoremediator of the red mud. Also, *Scirpus grossus* grown on synthetic bauxite mining wastewater is capable of accumulating main components of bauxite ores which are Fe and Al, while harbouring few resistant rhizobacteria [30,35].

Other characteristics of phytoremediator plants are overall ability to uptake and degrade contaminants in soils, endemic, non-agricultural crops and able to survive in harsh conditions such as high salinity and temperature [36]. Bioaccumulation factor (BF), bioconcentration factor (BCF) and translocation factor (TF) also play significant roles in determining the suitability of plants used for phytoextraction or phytostabilization [37,38]. BF refers to the metal concentration ratio of plants shoot to the soil, BCF refers to the metal concentration ratio of plants root to the soil, while TF refers to the metal concentrations of plant shoots to the roots [37]. Phytoextraction requires plants with high BF > 1 and sufficient biomass yield, while phytostabilization needs plants with high BCF > 1 and low TF < 1. Studies conducted by Mathiyazhagan and Natarajan [40] shows that *Vigna unguiculata*, *Jatropha curcas*, *Macrotyloma* *uniflorum*, *Vigna radiata*, *Gossypium hirsutum*, *Oryza sativa* and *Ricinus communis* have high metal transfer efficiency and are effective in uptaking Cd, Cr, Pb and Mn from bauxite waste dumps; proving them to be quite promising phytoremediators.

4. Rehabilitation of bauxite-mined sites

Lots of studies that have been done on remediation and rehabilitation of bauxite mining sites and its tailings, which also known as red mud. Although red mud shows to have deficiencies in some nutrients needed by plants, few researches conducted on revegetation possibilities on bauxite residues shows positive results which may lead to possibilities of phytoremediation of the red mud itself [40,41]. Two studies were conducted on the restoration of Jarrah forest in Western Australia and even though the rehabilitated sites were not becoming similar to the unmined forest, the various seed and fertilizer treatments were found to have long-term effects of vegetation attributes of the particular sites [42,43]. It was indicated that *Jatropha curcas* can be used as crop plants to remediate heavy metals such as Fe, Al, Cu, Mn, Cr, As, Zn and Hg [44–46]; thus, making it possible to remediate bauxite mining sites.

A practice done in Jamaica, which was reported by Jamaica Bauxite Institute [47] comprises of four-step technique in rehabilitating the bauxite mining sites. First, the mined-out areas were reshaped and striped-off topsoils were replaced. Then, the reclaimed areas were planted with pasture grasses to prevent soil erosion. After restoration has completed, inspection by authorities was done before the reclaimed land is used for farming, housing, community centres, schools or for light industrial building sites. These measures started back during 2004, as the mining regulations were amended to reassure post-mining rehabilitation processes [48].

Gao et al. [49] reported successful ecological restoration of Xiaoyi bauxite mine; located in Shanxi Province, China. Xiaoyi bauxite mine was restored using both engineering and biological reclamation techniques, which include land stripping technique, water engineering vegetation screening, crop varieties screening and land fertilization. These combined techniques resulted in a remarkable increase in organic matter, microbial activity reaching the level of a local farm field in 3 y cultivation period and soil fertility of arable layer reached the middle and upper level of local farm fields after 4 y of reclamation.

Meanwhile, Hinds [50] and Gardner [26] successfully rehabilitated bauxite mining sites in Western Australia under the mine rehabilitation programme by Alcoa World Alumina Australia. Early stages of the rehabilitation programme were unsuccessful as the techniques used were quite simple and inadequate. Stockpiled topsoil was respread and potential timber-producing trees were used to directly establish an early plantation. These trees suffered from inadequate root dispersion in the compact clay soil. A new technique of subsoil ripping was introduced to encounter the soil compaction problem, but this technique subsequently introduced rapid soil runoff and soil erosion problems. The rehabilitation programme was then successfully improvised, and the forest now harbours an estimated 780 plant species, with jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) as the dominating species. The improvised techniques include reshaping of the mined sites, recontouring of mined-out pits to mimic the original landscape, spreading and returning the topsoil to enhance the return of nutrients, organic matters and beneficial microbial communities; and returning of tree stumps, logs and rocks to provide early habitat of fauna. During the summer, the land is ripped and contoured. Then, a seed mix of different indigenous plant species is spread before the onset of autumn rain to maximize plant establishment. Fertilizer mix is applied with the help of helicopter during late autumn or early spring. And lastly, monitoring of the site is carried out to check whether the requirements of the establishment have been met and to inspect for erosion problems.

As phytoremediation help in remediating the contaminated lands from heavy metal pollution, it is might be best if the phytoremediation technique can be merged into a rehabilitation programme of mined sites. These might improve the rehabilitation programme as it can further naturalize the barren land.

5. Conclusion

Abandoned mining sites are unsightly, causing serious environmental and health concern in Malaysia. Phytoremediation is a promising and uprising technology in Malaysia. This review aims to provide a general overview of bauxite mining, its post-mining scenario, possible remediation technique and the cost involved in the rehabilitation of the mined sites. And more importantly, how past studies and success can be applied to help rehabilitate barren bauxite-mined sites in Kuantan. However, more studies need to be done to optimize the process thus fully utilize the potential of phytoremediation technology. With support from the government and private agencies, it will surely help in coordinating the efforts in improving environmental condition in Malaysia.

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