JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
Volume 8, Number 4 (July 2021): 2971-2984, doi:10.15243/jdmlm.2021.084.2971
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

Review

Future direction of Au agromining on how to solve artisanal and small scale gold mining problems

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Article history:
Received 19 May 2021
Accepted 7 June 2021
Published 1 July 2021

Keywords:
Au agromining
hyperaccumulators
ASGM
Indonesia

Abstract

Indonesia is one of the countries with the largest Au deposited. Gold mining has been the backbone of Indonesia’s economy. However, Indonesia also faces huge problems of Artisanal and Small Scale Gold Mining (ASGM) in a number of areas of Indonesia. A number of problems follow this Au mining method, including environmental, social and economic problems. Green innovation and technologies are needed to solve the problems. To date, Au agromining has been considered as a technology that can solve the numerical problems of Au conventional mining in the sector mentioned before. Gold agromining also has been proposed as a solution for the ASGM problem in Indonesia. However, until now, there have been no reports on the use of Au agromining technology in Indonesia. In fact, agromining research has been very advanced and is considered very prospective. This paper outlines the potentials of Au agromining to be implemented in Indonesia to overcome the social and environmental problems of ASGM.

To cite this article: Hamdan, A.M., Rahmi, R., Hafidz, A. and Rispalman. 2021. Future direction of Au agromining on how to solve artisanal and small scale gold mining problems. Journal of Degraded and Mining Lands Management 8(4): 2971-2984, doi: 10.15243/jdmlm.2021.084.2971.

Introduction

Indonesia is one of the regions crossed by the Cenozoic magmatic arc, which is the boundary of the Eurasian and Indo-Australian plates. This fact cause Indonesia has had a number of Au deposits (Syafrizal et al., 2017; Thomsen, 2017). Gold mining on Indonesia had begun since the 19^{th} century (Van der Eng, 2014; Leeuwen et al., 2014). Gold mining is spread across several islands including Papua, Sumbawa, East Kalimantan, Sumatra and Central Kalimantan (Leeuwen et al., 2014). Indonesia has very large Au reserves. In 2016, Indonesia was estimated to produce 4% of Au global and has produced 91 tons of Au. Proved Au reserve of Indonesia for placer gold is 15.5 tons, and primary gold is 2,626.7 tons (Performance Report of the Directorate General of Mineral and Coal, 2016). The mining sector, including Au mining, accounts for 6-12% of the gross domestic product (GDP) of Indonesia. This has made the Au mining sector one of the backbone of the Indonesian economy (Soelistijo et al., 2015; Spiegel et al., 2018). Until 2010, more than one million workers were involved in the mining sector of Indonesia. Indonesia is currently listed as one of the largest producers and exporters of Au (Topstad and Karlsen, 2015). Mining operations in Indonesia have encouraged employment opportunities, construction of infrastructure and development of remote areas. However, in the past decade, activities of artisanal small-scale gold mining (ASGM) are serious problems for Indonesia. In this method, the technique of Au extraction uses mercury (Hg) and/or cyanide (CN). Mercury has a high level of toxicity. Therefore, activities of ASGM are considered to threaten public health and environmental sustainability (Arifin et al., 2015). There is a total of 100-500 tons of Hg per year are estimated to be used for activities ASGM in Indonesia. That number causes Indonesia has been reported as the third-largest country that releases Hg to the environment in the two last decades after China and India (Spiegel et al., 2018). Activities of ASGM in Indonesia has also raised severe problems in other aspects, including politics, security, law, human rights, social and economic (Hentschel et al., 2003; Kumah, 2006; Bernhoft, 2012; Veiga et al., 2014; Macdonald et al., 2014; Northey et al., 2014; Calvo et al., 2016; Spiegel et al., 2018; Mutsvanga et al., 2018; Tayebi-Khorami et al., 2019; Levinson and Dimitrakopoulos, 2019).

The alternative technology and new innovation are expected to replace the ASGM method (Kumah, 2006; Wilson-Corral et al., 2012; Van der Ent et al., 2015; Basu et al., 2015). Those technologies must be effective, be economical and be environmentally friendly. To date, alternative technology that has these advantages is Au phytomining (Van der Ent et al., 2013; Krisnayanti et al., 2016). Au phytomining and/or Au agromining are the use of plants for extracting metals by three stages, including (i) cultivating of plants, (ii) extraction of Au into plant tissue (shoot), and (iii) processing of biomass to separate Au targeted. The term agromining refers to unproductive lands for food crops due to the land contains toxic metals (Krisnayanti and Anderson, 2014; Van der Ent et al., 2015; Kidd et al., 2018). Krisnayanti and Anderson (2014) and Krisnayanti et al. (2016) have proposed Au phytomining for the management of ASGM's tailing amalgamation. Subsequently, Krisnayanti et al. (2016) have shown that this technology can be carried out directly by the ASGM community in West Nusa Tenggara, Indonesia. Several laboratory studies and field trials have shown that this technology is more environmentally friendly and economical than the conventional method, especially on tailing waste management (Anderson et al., 2005; Sheoran et al., 2009; Wilson-Corral et al., 2012). Gold agromining is considered potential as a more integrated solution in social, economic and public health aspects to overcome the problem of ASGM's tailing management in Indonesia (Krisnayanti et al., 2016). However, there are some gaps in research for implementing this concept, especially for ASGM management. This paper describes those gaps and outlines the future direction of Au phytomining as a substitute for ASGM. The discussion focuses on Indonesia's case, but this projection can be widely applied.

ASGM in Indonesia

Artisanal and Small Scale Gold Mining (ASGM) is a term for informal Au mining by traditional technologies. This method can be carrying out by individual, groups or families (Krisnayanti et al., 2012; Krisnayanti, 2018; Puluhulawa and Harun, 2019). The stages of ASGM consist of amalgamation, tailings processing and gold recovery. These processes emit Hg into the environment. Besides Hg, some ASGM in Indonesia also uses cyanide (CN) (McDonald et al., 2014). In the process, ore processing is carried out by grinding using a roller. Then, Hg is mixed into ore to get Au-Hg amalgam. Amalgamation can be repeated several times until the Au in the ore is considered to be no longer extractable. The process results in tailings being dumped into the environment. To obtain the Au, the Hg in amalgamation is evaporated by heating. Thus, Hg can pollute the environment through (1) dissolved mine waste (Hg leached tailings) which then transported into the hydrological system, and (2) Hg vapour emissions into the atmosphere. Because of this process, ASGM has become the largest source of Hg pollution in the world (Azis, 2014; Macdonald et al., 2014; Esdaile et al., 2018; Puluhulawa and Harun, 2019).

Activities of ASGM have risks to nature and human. The miners of ASGM are nomadic communities. They build temporary shelters in sites of ASGM. The shelter is inadequate because it does not have a good sanitation system. In North Gorontalo, Hg had been found in the community's hair tissue higher than threshold levels. Because of that, many miners and communities have got health problem of the nervous system (Arifin et al., 2015 and Macháček, 2019). Basically, the communities and miners have known the risks of ASGM. However, economic motivation is more dominant than awareness of health risks that be faced (Basri et al., 2017; Trimiska et al., 2018).

Activities of ASGM have changed the function of agricultural land, changed topography, and disrupt the hydrological system. In Lombok and Sumbawa, activities of ASGM are carrying out around rice farming areas. Thus, the farming lands in that area have been contaminated by Hg on a very higher level than the threshold level. Besides that, several ex ASGM lands have been converted to cropland without remediation of Hg and CN that be released from amalgamation and cyanidation. The concentration of Hg within the soil of that land reaches 8,364 ppm (Krisnayanti, 2018).

ASGM has also caused many hydrometeorological disasters, including flood and landslide, then cause losses and casualties (Damanik, 2019; Plasmanto, 2019). One of the cases, in 2020, flood and landslide due to ASGM have occurred at Bogor, then because of this disaster, 21,742 people had to be displaced (Wisuda, 2020). However, Indonesia is one of the largest users of ASGM. The distribution points of ASGM in Indonesia is shown in Figure 1. The miners of ASGM are nomadic communities. They build temporary shelters in sites of ASGM. The shelters are inadequate because they do not have a good sanitation system. In 2010, more than 850 ASGM cites were found in 27 provinces.

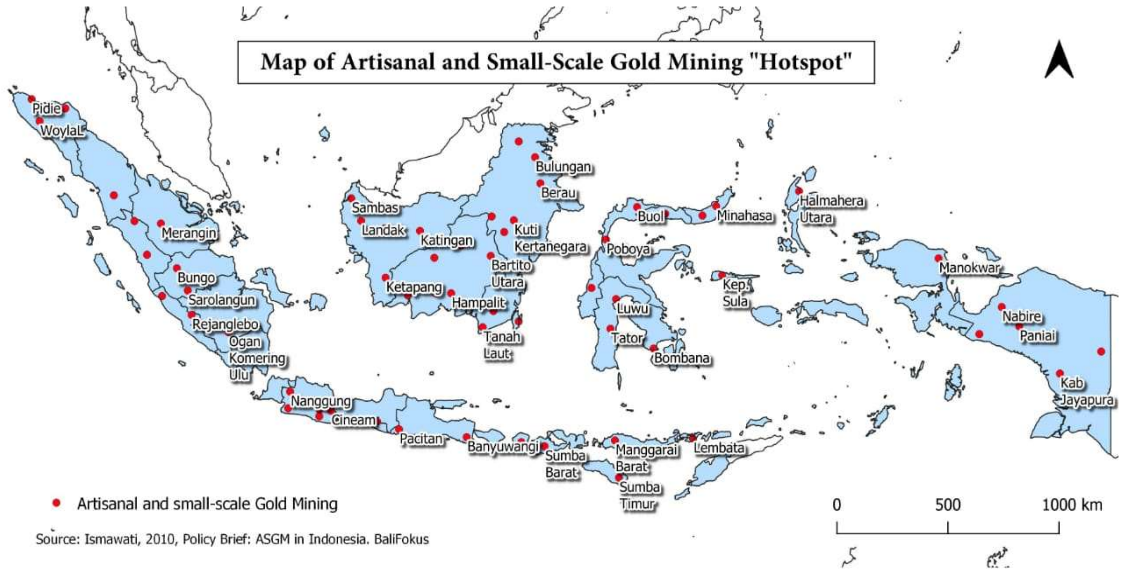

Figure 1. Distribution points of ASGM in Indonesia.

UNEP estimates that there are 300,000 miners of ASGM in Indonesia (Balifokus, 2013; 2015; UNEP Final Report, 2014). This problem cannot be viewed only from the perspective of public health. ASGM in Indonesia is a complex problem that deals with social, economic and political issues. ASGM has triggered social conflict in the sites. The conflicts consist of land grabbings, violence among communities and miners, and cases of gold grabbing (Al Zuhri, 2015). These conflicts due to lack of law enforcement, economic pressure of miners and/or communities and absence of clear and stick regulation for ASGM. Law enforcement is an effort for social control and also social engineering. Weak enforcement of regulations due to the government is faced with dilemma problems. ASGM has been considered as a source of livelihood who have no skills and skills. On the other hand, ASGM is considered as a more equitable approach to natural resources exploitation and provide direct benefits for society. Controlling ASGM is very difficult because most ASGM in Indonesia is illegal. Most ASGM in Indonesia is in rural areas where the condition of the people is still below the poverty line (Hentschel et al., 2003; Manus, 2005; Male et al., 2013; Krisnayanti et al., 2016; Puluhulawa and Harun, 2019).

The tending of communities to be ASGM miners is driven by several factors, including lack of employment, low education level of miners, community perceptions, and the low price of Hg. Most miners are people who live along the poverty line, and they do not have a good level of education. The low level of education cause miners to not have sufficient knowledge of public health and environmental sustainability. In addition, community perceptions in a number of locations assume that the job as an ASGM miner has been inherited from their ancestors. The other factor is the availability of cheap Hg. Indonesia has local mercury production, which has driven the price of mercury affordable for ASGM (Obiri et al., 2016; Redi, 2016; Spiegel et al., 2018).

However, ASGM has considered overcoming several economic problems. ASGM is an attractive alternative livelihood for rural workers because it has good potential to improve the wealth of a community. In general, ASGM has increased income and the availability of employment opportunities (Krisnayanti, 2018; Owusu et al., 2019). Therefore, ASGM should be regulated in such a way that regulations and policies are oriented towards environmental sustainability and public health. The Indonesian government has committed to regulating ASGM activities by considering all environmental risks that may arise, including by regulating the use of Hg. Several approaches have also been proposed to overcome Hg emissions from ASGM activities, including by breaking the mercury marketing chain (McGrew, 2016; Spiegel et al., 2018; Puluhulawa and Harun, 2019). In order to solve job opportunity and environmental problems simultaneously, green technology and new approaches for the community are needed.

Gold Agromining Technology

Since the ability of plants to extract the metals in a large amount into their tissues, the concept of phytoextraction has been developed to be more advanced, such as phytomining and phytoremediation. Phytoremediation is remediating contaminated land by using plants. Meanwhile, phytomining is minerals exploitation by also using plants. Phytomining has been considered to be prospective for future mining technology. This approach is environmentally friendly and inexpensive. The approach also can be used to be an alternative to replace conventional methods on certain land characteristics. The characteristics of that lands including low grade and uneconomic land that is mined by conventional methods and where is not accessible by heavy equipment. The term for phytoextraction on unproductive agricultural areas due to high metal content is agromining (Bani et al., 2007; Verbruggen et al., 2009; Callahan et al., 2012; Fernando et al., 2013; Orłowska et al., 2013; Boas et al., 2014; Van der Ent et al., 2015; Kidd et al., 2018). However, the term can be expanded for mining on land using crop technology and to be used by farmers or communities.

The term phytomining is used based on metal targeted. Gold phytomining is phytomining for Au as metal targeted. To date, Au phytomining was proposed as a method of processing tailings from the remaining gold metallurgical activities. The tailing can be originated from the company scale or ASGM scale (Wilson-Corral et al., 2012; Krisnayanti et al., 2016). The idea based on the fact that Au can be found within mine tailings and mine wastes at a high content level. The recycling capital needed is too high compared to the benefits obtained (Anderson et al., 1998). In addition, Au phytomining has also considered being economical to exploit a low grade auriferous. Low grades of auriferous can be found on several characteristics of land, including (i) lands that are not economical due to the reduction of reserves, (ii) lands with auriferous that are not economical to exploit, and (iii) waste mining lands that are not economical to process (Wilson-Corral et al., 2012; Kivinen, 2017). Anderson (2005) argued that the use of the term "mining" in explaining the ability of plants to extract metals from the soils is a misconception. This method is not considered a competitor for conventional mining (Anderson et al., 1998). However, the term agromining in some literature is still relevant because this technology can be a substitute for conventional methods on lands with certain characteristics (Van der Ent et al., 2013; Van der Ent et al., 2015; Kavanagh et al., 2018).

Gold hyperaccumulator

The plants that to be used in agromining are called hyperaccumulators or hyperaccumulating plants. These plants can absorb heavy metals in high concentrations into the tissues. In biological science, heavy metals refer to metals or metalloids needed by organisms but in very low concentrations. The metals and metalloids then become toxic if they accumulated to the tissue in higher concentrations threshold are they have (Rascio and Navari-Izzo, 2011). However, a hyperaccumulator can absorb metals on a higher level of toxic level threshold (Sheoran et al., 2013; Sobczyk et al., 2017). The kind of hyperaccumulator can be grouped by the metal they accumulate. So, hyperaccumulating plants for Au are called Au hyperaccumulators. Gold hyperaccumulators are all plants that can absorb Au higher than 1 µg/g of dry biomass (Anderson et al., 2003).

In the beginning, the presence of Au in plant tissues was suspected to be an indicator of Au exploration (Brooks 1982; Girling and Peterson, 1980). Some plants have been discovered to accumulate Au, such as *Pseudotsuga menziesii, Pinus banksiana, Picea mariana, Hordeum vulgare* and *Phacelia sericea* (Shacklette et al., 1970; Bali et al., 2009). The mechanism of Au accumulation into the foliage is still not fully understood. In general, Au into the tissue consists of 1) solubilization of Au of the soil matrix, 2) gold uptake into the root of hyperaccumulator, 3) transport to the shoots, detoxification and sequestration in the tissues of hyperaccumulator (Sheoran et al., 2013). Gold in *Brassica juncea* is accumulated in the form of biogenic particles in the carbon matrix (Anderson et al., 2013). The mechanism of Au accumulation has not been deep as understanding for mechanisms of Ni or Zn accumulation (Reeves and Adigüdzel, 2008; Deng et al., 2018).

Furthermore, the use of these plants has been developed as mining technology, as we described before. To date, *Brassica juncea* and some crops such as carrots, onions, red yams and turnip have been used in simulations of the implementation of gold phytomining in the field (Msuya et al., 2000; Anderson et al., 2005). In the practice of Au agromining, the use of local species is a key factor in the success of Au agromining. This is because of the adaptation ability of local species to the soil and climate conditions. In addition, the use of non-native species has the potential to disrupt local biodiversity (Prasad and Freitas, 2003; Ghosh and Singh, 2005; Prasetya et al., 2010).

The processes of Au accumulation by plants are affected by both biological and physical factors. The factors are including bioavailability, rhizosphere, plant interactions with microbes, root exudation and plant transpiration (Gove et al., 2002; Gardea-Torresdey et al., 2005; Wilson- Corral et al., 2011; Wilson-Corral et al., 2013; Reith et al., 2013). Although transpiration is affecting gold transport in plants, in some species, transpiration factors do not look significant (Girling and Peterson, 1980). The ability of the hyperaccumulator to absorb Au is also determined by the solubility of gold in the soil.

In natural conditions, Au has a low solubility. Therefore, the addition of injection fluid is a decisive step in Au agromining (Anderson et al., 1998; Gardea-Torresdey et al., 2005; Wilson-Corral et al., 2013; Reith et al., 2013). To date, a plant that naturally absorbs Au to the tissues in high-level concentration has not been found. The accumulation of Au needs fluid injection uptake Au from ore to the tissue. Gold hyperaccumulator is unlike Ni hyperaccumulators that can accumulate Ni naturally without fluid injection. However, a certain chemical can stimulate Ni absorbtion.

Table 1. The list of Au hyperaccumulators, the concentration of Au in the foliage, and chemical induction list.

Species	Au (µg/g)	Author	Chemical Induction
Brassica juncea	0.37-57.2	Anderson et al., 1998; Anderson et al., 1999; Lamb et al., 2001	NaSCN, KBr, KCN, KI, $(NH_4)_2S_2O_3$.
Chicory	0.07 -1.19	Anderson et al., 1998; Anderson et al., 1999; Lamb et al., 2001	NaSCN, KBr, KCN, KI
Impatiens sp	3.09	Anderson et al., 1998; Anderson et al., 1999	-
Arrhenatherum elatius	0.07 - 1.43	Anderson et al., 1998; Anderson et al., 1999	-
Daucus carota L		Msuya et al., 2000	thiocyanate; thiosulfate
Alluim cepa L.		Msuya et al., 2000	thiocyanate; thiosulfate
Beta vulgaris L		Msuya et al., 2000	thiocyanate; thiosulfate
Raphanus sativus		Msuya et al., 2000	thiocyanate; thiosulfate
Oriental radish		Msuya et al., 2000	thiocyanate; thiosulfate
Tobacco	1,2	Krisnayanti et al., 2016	NaCN
Paspalum conjugatum	601.9	Handayanto et al., 2014	ammonium thiosulfate
Trifolium repens	27,000	Piccinin et al., 2007	ammonium thiosulfate
Helianthus annus	119,000-141,000	Wilson-Corral et al., 2012	NaCN
Chilopsis linearis	18,000	Gardea-Torresdey et al., 2005	NH_4SCN
Sorghum halepense	31,000	Rodriguez-Lopez et al., 2009	NaCN
Trifolium repens L. cv. Prestige	> 27,000	Piccinin et al., 2007	NaCN
Medicago sativa L. (alfalfa)	40,900	Gardea-Torresdey et al., 1999	thiourea
Kalanchoe serrata	21,700	Gardea-Torresdey et al., 1999	thiosulphate
Zea mays L	600	Anderson et al., 2005	*Zea mays* L
Barceya coddi	97,000	Lamb et al., 2001	NaSCN, KCN

Gold agromining cultivation techniques

Cultivation of agromining has two main aspects. These are the selection of species and cultivation methods. The candidate of species should be resistant to conditions of temperature, water stress, salinity and pH. Therefore, the plants suggested being used are endemic or native species. In addition, an effective species has a short duration of growing and have a large amount of biomass (Anderson et al., 2005; Sheoran et al., 2013).

In practice, cultivation aspects consisted of characterization of soils, drainage systems, planting systems, injection fluid selection and fertilization (Keeling et al., 2003; Anderson et al., 2005; Hunt et al., 2014). The effect of soil moisture has been investigated on the amount of biomass production. This parameter is linear to biomass production (Wilson-Corral et al., 2012; Nkrumah et al., 2018). For cultivating ore tailing, Swaroop et al. (2013) have successfully used gold ore tailing as media for *Brassica oleracea* and *Brassica oleracea* var. Capitata. This result indicates that fertilization must consider the micronutrient content of ore. The minerals content of the soil will affect the pH value of soils. Then, the value of pH greatly affects the ability of plants to accumulate metals (Gramss et al., 2004). For Au extraction, the optimum pH is 8.9-9.5 (Wilson-Corral et al., 2012). But, Au can only be dissolved and then form complexes in low pH soil conditions. Meanwhile, Au is insoluble in the soil. This fact has made Au agromining has bigger limitations than Ni agromining technology (Shooran et al., 2013; Ali et al., 2017). So, on Au extraction, a chemical fluid is needed to inject Au into the foliage, but the addition of fluid induction has the potential to affect the soil characteristic, including pH, microbial life and potentially cause destructive of soil quality (Lamb et al., 2001; Grčman et al., 2001). That is a challenge for cultivating Au agromining, because biomass production factor, accumulation of Au factors and environment management factors are important aspects to be considered.

Therefore, the selection of chelation agents is a crucial factor in cultivation (Wilson-Corral et al., 2012). A number of chemical liquids have been considered to be the potential induction fluids, as shown in Table 1 (Gardea-Torresdey et al., 2005; Wilson-Corral et al., 2012). However, the safety control for the environment has to get more attention because some fluids injection have a high level of toxicity, such as potassium cyanide (MacDonald, 2015; Ali et al., 2017; Jaszczak et al., 2017).

The transpiration rate is considered to be one of the success factors of phytoextraction (Leitenmaier and Küpper, 2013). However, hyperaccumulator transpiration is known to be influenced by genotype and/or evolutionary factors. Ecotype factors include morphological characteristics, width and thickness of leaves and number of stomata. Meanwhile, climate conditions are thought to be the cause of genetic evolution in order to adapt to local climate (Lu et al., 2008; Wan et al., 2015).

Biomass processing

Several methods have been proposed and implemented in the processing of hyperaccumulator biomass, such as composting, combustion, gasification and hydrometallurgy (Mohanty, 2016; Simonnot et al., 2016). On processing of Ni biomass, since Lamb et al. (2001) found that leaching by using HCl is non-green and expensive, further ideas had been investigated. Base on an experiment, the processing of *A. muralle'*s biomass by leaching indicates 0.5 M H_2SO_4 at 90°C could extract 97.0 ± 6.8% of Ni. According to Barbaroux (2009), hydrometallurgy is more economical than the combustion method. However, using hard acid is considered a non-green method and trigger a new environmental problem. Both the cost and sustainability aspects are the main consideration to find the method of biomass processing. According to Krsinayanti et al. (2016), the hydrometallurgy approach for Au biomass processing is not economically promising. Furthermore, Krisnayanti et al. (2016) proposed processing tobacco biomass with ashing and smelting using borax. This method has been simplified to save reagents and decrease the costs (Wood et al., 2006; Losfeld et al. 2012; Simonnot et al., 2016; Chaney and Baklanov, 2017).

Implementation Au agromining to Substitute ASGM

Opportunities for implementation of Au agromining in Indonesia are supported by several factors, including: (1) Indonesia has high biodiversity; thus, the opportunities to find the Au hyperaccumulators are enormous; (2) Indonesia has a tropical climate, so the hydrological system, soil moisture and plant transpiration rates support the cultivation of the Au hyperaccumulators; and (3) The abundance of auriferous deposits in Indonesia so Au mining activities in Indonesia have the prospect to continue to be developed. On the other hand, the Indonesian government provide a continuous irrigation system to reach all areas of national agriculture.

A field for Au agromining should be designed by several considerations, including environmental safety and effectiveness of Au agromining processes. The chemical injection used is the major issue of environmental safety. Therefore, according to this issue, the land's design must follow specific conditions, including (i) the land system does not emit heavy metal to the environment such as surface water, groundwater, soil and air, and (ii) the land has a good drainage system that can localize the induction fluid used (Wilson-Corral et al., 2012). For this consideration, the aquaculture lining system is the best candidate to be adopted in the agromining system (https://www.climaxindia.com/aquaculture.html).This system has been used in various fields of agriculture and is considered to be able to increase the productivity of agricultural products.

Cultivation of plants can be carried out either ex-situ or in-situ. For ex-situ cultivating, the stages consist of (i) ore crushing, (ii) land preparation (iii) installation of liner layers (iv) ore transportation (v) land management (vi) planting (vii) maintenance and (viii) harvesting. But for in-situ, the stages consist of the same steps as the ex-situ except for the ore transportation stage. The choice of whether to be implemented ex-situ or in-situ depends on the characteristics of the land, the availability of land, the source of water for cultivation and environmental factors. According to Krisnayanti et al. (2016), agromining is better if it is done on flat land because the drainage system will be more effective and efficient to be designed on this characteristic land.

In addition to technology development, another challenge is the acceptance of the community to this technology. Krisnayanti et al. (2016) have conducted an experiment of Au agromining for amalgamation tailing of ASGM management in Indonesia. According to Krisnayanti et al. (2016), the ASGM community was very sceptical to Au agromining technology. This is because the community considers that ASGM more has economic benefits instantly, in contrast to agromining, which takes 3 to 4 months for harvesting. In addition, crop cultivation has the risks of crop failure and additional costs that are not required by conventional methods. Therefore, the agromining implementation as a substitute for ASGM requires a socialization approach, strengthening commitment and reward (Goodman and Griffith, 1991). The approaches are also based on political, regulatory, social and economic policies.

To date, tobacco, maize, sunflower and cassava have been tested as local plants that can be used as accumulators for Au Agromining (Krisnayanti and Anderson, 2014; Krisnayanti et al., 2016). Based on the number of species that have been tested, local Indonesian species for Au extraction have not been identified massively. Currently, Au hyperaccumulators are also still much less when compared with the number of Ni hyperaccumulators that have been identified (Reeves et al., 2017; Sobczyk et al., 2017). However, the discovery of Indonesian native or endemic species for Au agromining has enormous opportunities. The geographical conditions make Indonesia the centre of world biodiversity. 28,000 plant species are estimated to grow in the Indonesian territory. This number makes Indonesia a megadiversity country (Astirin, 2000; Sastrapradja, 2005; Rintelen et al., 2017). There are two basic choices for species to be cultivated, namely the ability of plants to survive in the environment and economic factors. The species chosen should be species that are already local varieties commonly commercialized among farmers. This is because farmers already expert cultivation techniques well compared to non-local species or which are not local varieties that are often cultivated (Krisnayanti et al., 2016).

Gold Agromining as Solution for Problems of ASGM

Gold agromining has been proposed as an approach for tailing management and beneficial purposes simultaneously (Sheroan et al., 2013). Based on the aspect of Au agromining as described before, this approach has the potential to be used for substitute ASGM. That is because the main technology is adopted from agriculture technology that is very familiar to the community, especially in agrarian countries. There is some addition and difference technique, but the framework is not different. Therefore, this technology has the prospect to be applied neither individually nor group farmers.

Gold agromining as a candidate of substitute of ASGM must occupy sustainability principles that have been proposed by The International Council on Mining and Metals (ICMM). These principles have been proposed for waste mining management. According to Tayebi-Khorami et al. (2019), those principles can be summarized in five key aspects, including social dimensions, geoenvironmental aspects, geometallurgy specifications, economic drivers, and legal implications into five integrated areas. The principles are hoped can overcome the problem comprehensively to some various aspects and perspectives (Basu et al., 2015). However, the principles and key aspects can be adopted to assess Au agromining as a substitute for ASGM.

Economic aspect

Mining has to be a driver for a circular economy (Tayebi-Khorami et al., 2016). In addition, the benefit distribution on Au deposit also one of the issues that can trigger a social problem. In Indonesia, as a developing country, sharing of economic values of Au mining that is carried out by corporation has been a national issue. A large number of ASGM on-site with Au abundance is evidence that the natural resources do not have an economic impact on society directly. Gold exploitation that has been carried out by mining company has considered can not have an economic impact directly on society. This is due to conventional mining need a large capital, and it also only can be carried out by conglomeration.

Based on that issue, new technology is needed which can distribute economic values directly to society. Gold agromining will give the new economic impact, including: giving job opportunities, land use optimization, the emergence of biomass processing plants, the emergence of chemicals distributors for Au agromining, the emergence of biomass and its processing products distributors, and the emergence of new industries that utilize Au agromining results that were not there before. The stages of Au agromining can be grouped on land preparation, cultivating, Au production and Au marketing. Each group has the potential to create a new job opportunity. On land preparation, the new job is surveying service, economic analyst, soils and ore analyst, soil and irrigation preparation. Cultivating for Au phytoextraction is one of the choices for the farmers in utilizing their land. This "agriculture" can be chosen if Au agromining is a higher benefit than the other agriculture commodities. Because of that, the companies of biomass processing will be needed for Au production. So, all of the stages are going to create a circular and distribution economy, as shown in Figure 2.

To analyse the economic feasibility of Au agromining as a substitute for ASGM, the study has to consider several factors including predicted annual costs, irrigation, fertilization, plant protection and harvesting; land costs; biomass and its processing, fluid injection, price of the metal, and the value of alternative land uses. This technology is considered to be economical for the processing of auriferous tailing and rock waste of Au mining (Wilson-Corral et al., 2012). But, to extract Au from amalgamation tailing, this method has no conclusion about the beneficial aspect (Krisnayanti et al., 2016). Wilson-Corral et al. (2012) have estimated the net profit obtained of Au agromining is US $15,098/ha. The economic benefits based on Au content in biomass assuming 8330 kg/ha of dry biomass (Wilson-Corral et al., 2012) are presented in Figure 2a. The benefit based on the amount of biomass produced assuming Au content in plants is 55 mg/kg (Anderson et al., 2005) is presented in Figure 2b. Meanwhile, by summarizing the mathematical model proposed by Anderson et al. (2005), the correlation between the concentration of Au in biomass and that contained in the soil is $Y = a \ln(x) + C$, where a and C are constants that depend on the species and the induced fluid used, Y is Au concentration in biomass and x is the Au concentration in the soil. Economic benefits based on the Au concentration function in the soil (Anderson et al. 2005) are presented in Figure 2c. Indonesia's per capita income is US $ 4175 per year, so based on Figure 2a, to get a profit above per capita income, the breaking point is around 4000 kg/ha/year of biomass.

The report of Krisnayanti et al. (2016) indicates that Au-phytomining is still an expensive practical to process ASGM tailing. So, the technique still needs to be developed. Further studies are still required to advance to find a cheap fluid injection, a cheap method of biomass processing, and an efficient method of cultivation for maximum benefit. For these purposes, the studies have been still limited. The differences result from these benefit due to the land, ore characteristics, species and cultivation methods are different for each case.

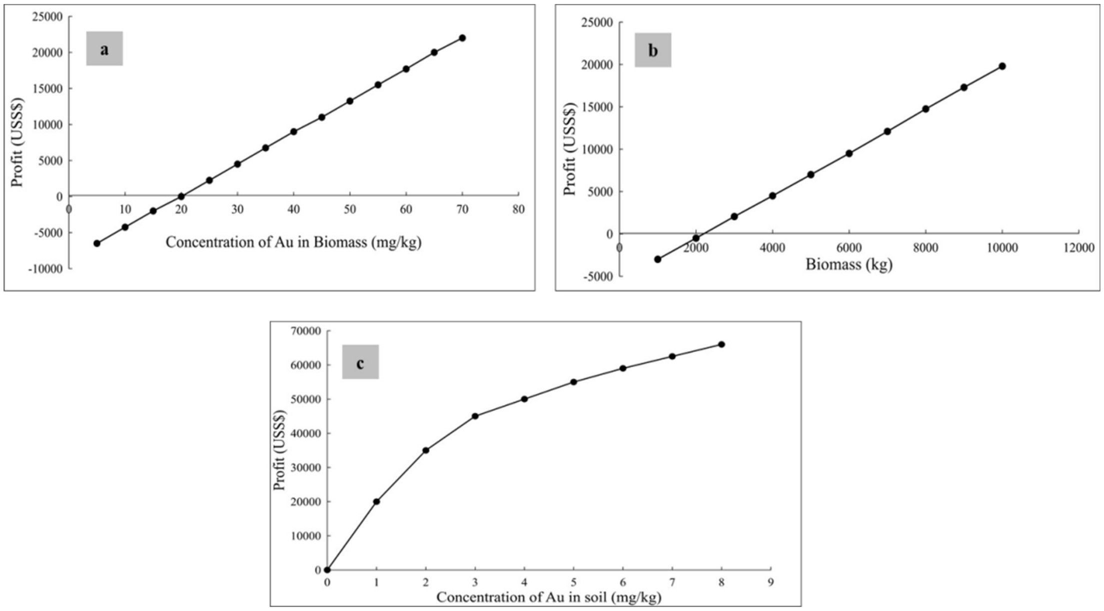

Figure 2. Simulation of profits based on Wilson-Corral (2012) analysis. a) Profit based on level of Au content in the biomass by the assumption that dry biomass is 8,330 kg/ha. b) Profit bases on the amount of biomass by Au content in the dry weight of 55 mg/kg. c). profit based on the function of Au concentration within the soil (Anderson et al., 2005).

That indicates that the wide practical of Au agromining to substitute for ASGM need massive testing and trial. The testing and trial also have to consider the user's aspect. The capital scale and user model is determined the technique that to be used. For example, traditional farmer and farmer group as the user will have a different approach for practical of this method.

Geoenvironmental aspect

Waste management of Au mining is a major issue of geoenvironmental aspect of conventional mining. Gold phytomining has been proposed as a technology for waste management. This approach has been considered as a technology that is more economical to recycle both waste rock and waste tailing of metallurgical processes. The environmental problem of leaching for low-grade waste can be reduced by Au phytomining.

Because the model of Au extraction that used is phytoextraction, Au agromining has a lower environmental issue. Gold agromining does not release waste tailing like ASGM. Although, Au agromining is not free-waste mining. Gold grade of auriferous is going to be decreased and in the end, the ore is not still economical. As a substitute for ASGM, waste auriferous management has to be developed for a sustainable environment.

Au agromining has been gotten a critic for using fluid injection to extract Au from the auriferous. However, if this using compared to conventional recycle tailing, the chemicals used are lower. This issue also has to be got attention for its using for farmer/miner of Au agromining. The technique of land preparation has to be designed for keeping fluid injection, and the heavy metals have no emission to the environment. For the fluid injection excess, bioremediation has been proposed to overcome the problems. For example, for cyanide, several groups of microorganism have been discovered for biodegradation, including bacteria such as *Klebsiella oxytoca*, *Pseudomonas fluorescens*, fungus such as *Fusarium solani*, *Fusarium oxysporum* and algae such as *Scenedesmus obliquus*.

Simultaneously, Au agromining can be a technique to restore the environmental destruction of mining, both ASGM and conventional mining of a company. The agricultural land can be restored that has been decreasing because of ASGM activities. Land reclamation is expected to restore lost economic resources such as agricultural sectors. Some hyperaccumulating plants are known to have phytoextraction ability to multiple metals. There is a possibility that Au and Hg accumulation occurred simultaneously so that phytoextraction can be multifunctional. In addition to Au exploiting, these plants are also expected to be used in removing Hg from the land. Some species that grow in ex-Au mining field in Indonesia have been considered as potential species for Hg remediation from the soils, including *Paspalum conjugatum* (Muddarisna and Krisnayanti, 2015), *Lindernia crustacea, Digitaria radicosa* and *Cyperus kyllingia* (Muddarisna et al., 2013).

Metallurgical aspect

Metallurgy not only involves mining and metallurgical field but can also be integrated into environmental and economic aspects. Gold biomass metallurgy is more economical and less environmental impact because biometrics of Au is not complex as conventional ore. Bio-ore needs more low energy, then cheaper than conventional mining. Because of the selective accumulation of metal into the plants, bio-ore has fewer contaminants than conventional ore. In addition, bio-ore also does not contain sulfides. Thus, its processing does not contribute sulfur emissions into the atmosphere. Acid rain can cause serious problems for the environment and human health (Semrau, 1971; Sheoran et al., 2013; Van der Ent et al., 2015; Schrama et al., 2017). Therefore, metallurgical processes of bio-ore are greener than metallurgical processes of conventional ore. Besides that, biomass processing research has the potential to find other products besides pure Au. Nickel biomass processing has been directed for Ni salt products and various other products (Wood et al., 2006; Losfeld et al. 2012; Simonnot et al., 2016; Chaney and Baklanov, 2017).

Social dimension

Gold mining and its waste management must not trigger a social conflict. A social conflict can occur among traditional miner, illegal companies, government or security forces, and community (Rahim, 2017). The rising of conflicts has resulted from various conflict of interest between stakeholders (Miall et al., 2000). Community resistance to the activities of ASGM is an effort to keep the environmental sustainability from activities of mining. For example, in 2011 shooting occurred to the man due to the existence of mining activity in Mandailing Natal, North Sumatera (Ramadhan et al., 2014). Wahyudi and Slamet (2015) investigated response community who live in sites of ASGM; generally, the community in sites of mining reject activities of ASGM. Meanwhile, conflicts between miners of ASGM triggered by the grab of land and access to the auriferous site. Besides of advantage on the environmental aspect mentioned before, Au agromining has a lower risk of conflict. Because the activity of Au agromining is like the activity of agriculture; therefore, the use of agricultural land has legality of ownership. Activities of Au agromining have a high potential to occurred share value between communities, such as land leasing. Social conflict also can be reduced due to, as an agrarian country, Indonesia has set regulations of land that will encourage the orderly implementation of Au agromining.

Legal dimension

The legality of ASGM in Indonesia reaps the pros and cons. Some local governments prohibit ASGM activities by considering the highly destructive environmental impacts. But part of it is permitted because it will bring jobs and community welfare. Because Au Agromining does not emit Hg into the environment and can prosper the community, Au Agromining will not reap the pros and cons of the legal aspects.

Conclusion

Au phytomining is the future technology to solve the problem of ASGM in Indonesia. The problem aspects that are overcome by Au phytomining Au are shown in Figure 3. However, further research is needed to develop this technology, both in the aspects of cultivation, biomass processing and implementation studies.

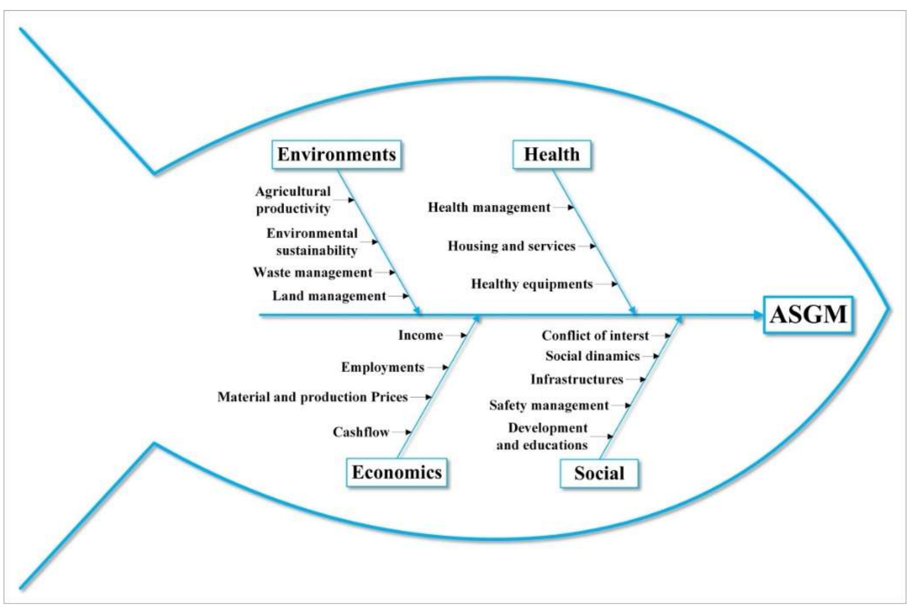

Figure 3. Diagram of problem-solving to environmental sustainability issues of ASGM.

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