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Potential use of coal ash as growing media: Effect on the plant's growth and future estimation for land reclamation

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KEYWORDS

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ABSTRACT

Coal ash, such as fly ash (FA) and bottom ash (BA) is mostly generated from a Coal-fired Steam Power Generation (PLTU) process. An increase in the number of PLTUs in Indonesia is proportional to the high volume of FA and BA generated, causing adverse environmental impacts if not properly treated. Various studies have highlighted the potential valorization of FA and BA, including building materials, cement ingredients, concrete, and growing media. This study aimed to evaluate the potential use of FA and BA as a growing media and to explore the potential future application for reclamation of heavy-metal-contaminated (or ex-mining) land. The results showed that composting FA with blackwater sludge (BWS) and rice straw (RS) produced compost that complied with the targeted standard. The addition of FA, BA, and composted FA in the growing media impact the growth and Zn adsorption ability of the dwarf elephant grass (*Pennisetum purpureum* cv. Mott). However, the composted FA has superior performance in general as a growing media. The future estimation of the application FA and BA combined with domestic waste (blackwater and greywater) for reclamation of ex-mining land is proposed. By integrating the phytoremediation ability of the grass plants and the biorefinery approach, the proposed future estimation may provide a sustainable valorization pathway of FA and BA for heavy metal-contaminated or ex-mining land reclamation. Thus, transforming FA and BA as a component of growing media could reduce the potential risk of heavy metals distribution into the food chain and the surrounding environment.

Introduction

Coal ash, categorized as fly ash (FA) and bottom ash (BA) are coal combustion residues produced by power plants (Jayaranjan et al., 2014) or municipal solid waste (MSW) incineration plants (Assi et al., 2020), with a production of around 0.75-1 billion tons annually (Yao et al., 2015). According to the Secretariat General of the National Energy Council (2016), in Indonesia, domestic coal consumption by Coal-fired Steam Power Generation (PLTU) was 70 million tons (80.72%) in 2015. The Directorate General of Electricity (2019) reported that coal demand for power generation amounted to 82.2 million tons (in 2017) and is expected to increase to approximately 162 million tons (in 2027). The increase in coal consumption is in line with the increase in PLTU development in Indonesia. Thus, it is estimated that around 10 million tons of solid waste can be generated annually in the form of FA and around 2 million tons of BA. In general, the chemical content of FA is almost the same as BA, but BA contains more carbon than FA (Ramme and Tharaniwil, 2013), as shown in Table 1.

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Table 1. Composition of FA and BA from different types of coal

Compounds	Types of coal		
	Bituminus	**Sub-Bituminus**	**Lignit**
		Fly Ash (FA)	
SiO_2 (%)	20 – 60	40 – 60	15 – 45
Al_2O_3 (%)	5 – 35	20 – 30	10 – 25
Fe_2O_3 (%)	10 – 40	4 – 10	4 – 15
CaO (%)	1 – 12	5 – 30	14 – 40
MgO (%)	0 – 5	1 – 6	3 - 10
SO_3 (%)	0 – 4	0 – 2	0 – 10
Na_2O (%)	0 – 4	0 – 2	0 – 6
K_2O (%)	0 – 3	0 – 4	0 – 4
LOI	0 – 15	0 – 3	0 – 5
		Bottom Ash (BA)	
SiO_2 (%)	61.0	46.7	-
Al_2O_3 (%)	25.4	18.8	-
Fe_2O_3 (%)	6.6	5.9	-
CaO (%)	1.5	17.8	-
MgO (%)	1.0	4.0	-
Na_2O (%)	0.9	1.3	-
K_2O (%)	0.2	0.3	-

Source: Ramme and Tharaniwil (2013)

Dermawan and Ashari (2018) stated that, based on PP No 101 of 2014, FA and BA are included in the category of toxic and hazardous waste (also known as B3 waste) due to their content of heavy metal elements exceeds that of the standard limit. Therefore, FA and BA have the potential to cause environmental pollution and require extensive stockpiling of land (Menéndez et al., 2014). Stockpiling FA and BA without further waste treatment may harm the surrounding environment, especially if there is leaching due to rainwater. Thus, harmful metals (such as Pb, Cd, As, Hg, etc.) will be released into water bodies and contaminate water, animals, and aquatic plants that will be consumed by humans (Dindi et al., 2019). Furthermore, the heavy metals and trace elements in FA and BA can accumulate in groundwater or surface water and enter the food chain, causing damaging effects on living organisms and human health (such as cancer or respiratory disease) (Jambhulkar et al., 2018). Thus, such conditions may significantly reduce the quality of the environment and the safety of living organisms.

However, the newest regulation of PP No. 22 of 2021 has no longer classified FA and BA as B3 waste and highlighted their utilization or application (The Ministry of State Secretariat Republic of Indonesia, 2021). The valorization of FA and BA into high-value added products is essential to reduce the number of FA and BA reservoirs, disposal costs, and disposal permit requirements, as well as reduce the negative environmental impact (Mushtaq et al., 2019). Furthermore, many studies have emphasized that FA and BA have a high potential to be valorized into high-value products due to their mineral contents (i.e. silica, iron, or other trace metals) and their characteristics (i.e. hydrophobic and granular size) (Hemalatha and Ramaswamy, 2017; Sahoo et al., 2016). Furthermore, the minerals in FA and BA are considered inert materials because of the high-temperature incineration process, thus non-hazardous for further utilization (Jayaranjan et al., 2014). A previous study reported that FA and BA contain silica and aluminum, thus they can be used as a material to manufacture geopolymers (Deraman et al., 2015). Many studies have reported several uses of FA and BA, including as an absorbent in wastewater treatment (Jayaranjan et al., 2014; Mushtaq et al., 2019); materials for the manufacture of foam glass (Li et al., 2018); building and road materials (Kieckhäfer et al., 2016); lightweight aggregates (Jayaranjan et al., 2014); and mixture for concrete (Dermawan and Ashari, 2018). For example, James and Ifelebuegu (2018) found that FA can remove detergent content in greywater. These findings indicate that valorization of FA and BA into high-value added products can potentially provide economic benefits, and, more importantly, can provide positive impacts on reducing the environmental pollution.

Several studies have also reported the use of FA and BA as substitutes for fertilizers and growing media for horticultural (agricultural) commodities, forestry, and ornamental plants, as well as on degraded soils or land (Jagodzinski et al., 2018; Mahale et al., 2012; Noviardi, 2013; Sormunen et al., 2016; Wardhani et al., 2012; Weber et al., 2015). This is because FA and BA contain essential nutrients (such as P, S, K, Ca, Mg, Cu, Mn, and Zn), which are critically beneficial for plant growth or microorganisms in the soil (Shaheen et al., 2014). A previous study by Mahale et al. (2012) stated that FA could be used as a mixture of growing media in pots with a ratio of 10-60% (w/w). Some of the plants used are wheat (*Triticum aestivum*), green beans (*Vigna radiata*), and black lentils (*Vigna mungo*). The results showed that using FA as a growing media could increase seed germination. The study also reported that heavy metals (such as Fe, Mn, Cd, Cu, Mg, Ni, Pb, and Zn) were only accumulated in plants at very low concentrations and still below the permissible limits for human consumption. Wardhani et al. (2012) found that using FA as a growing media mixed with *Lembang* soil at a ratio of 25:75 and 50:50 was able to increase the growth rate of tomato plants without any symptoms of toxicity. Noviardi (2013) also reported that adding 50% FA in compost, as a growing media, increased the growth of sunflower plants, possibly due to FA contains metals or ions that have the potential to act as a soil enhancer and source of nutrients. Sormunen et al. (2016) reported that using BA as a component in growing media positively enhances plant growth. Jagodzinski et al. (2018) also emphasized that using FA and BA as components in the growing media can recycle beneficial metals and nutrients for plant's growth, and prevent contaminants from re-entering the environment. Thus, valorizing FA and BA as fertilizer substitutes and/or growing media may potentially minimize severe negative impacts and carbon emissions to the environment due to synthetic (or chemical) fertilizers.

Although FA and BA contain organic compounds, the supply of nitrogen compounds is still inadequate. Thus, their use need to be optimized by adding organic compounds with low C/N ratios at the early stages of the land reclamation process (Pinto et al., 2018). The addition of organic compounds aimed to increase the diversity and number of microbes that grow in the reclaimed land. Previous research by Ram and Masto (2014) found that using FA as a growing media by mixing with various organic substrates (such as animal manure, poultry manure, sewage sludge, and compost) was proven to increase the quality of soils. Their study also reported that adding manure to FA provided a superior quality compared to that of other organic materials.

Domestic waste is one of the most common types of waste in Indonesia, and it is classified into two types: blackwater (which includes feces, urine, and flush water) and greywater (which includes wastewater from the bathroom, laundry, and kitchen), both of which contain a high level of organic matter (Sharma and Kazmi, 2015). Various studies have highlighted the use of blackwater and greywater. Research by Tervahauta et al. (2014) showed that the application of blackwater sludge (BWS) reduced heavy metals contamination in the soil.

Thus, blackwater can be an alternative option to replace the use of inorganic fertilizers or manure fertilizers. Furthermore, blackwater can also be used as a growing media due to its high content of macro-nutrients (such as N, P, and K), micro-nutrients (such as Zn, Cu), non-essential metal elements (such as Cr, Ni, Pb, Ca, and Hg) needed by plants for growth (Ranasinghe et al., 2016). Mulec et al. (2016) stated that blackwater can be used as a growing media through a composting process with other organic wastes such as sphagnum peat, bark, and wheat grain. Various studies have reported that greywater can be recycled and used for flushing toilets, irrigating home's garden, firefighting, cooling, and washing on a commercial scale industry (Dwumfour-Asare et al., 2018; Maksimović et al., 2015; Shamabadi et al., 2015). Greywater also has potential as a growing media (Kotsia et al., 2020; Pradhan et al., 2019; Wurochekke et al., 2014). For instance, Astuti and Sriwuryandari (2016) found that using greywater as a growing media for vetiver grass increased the number of roots, height, and thickness of the stems. Furthermore, Agra et al. (2018) have also investigated the use of greywater as a growing media for *Phyla nodiflora* and *Convolvulus mauritanicus* with positive results.

Research on combining FA and BA with other organic materials as growing media is still limited. For example, Sondari (2011) stated that a mixture of BA and organic waste (i.e. chicken manure, straw, rice husks, and bran), also known as BA *bokashi*, is also effective for use as a growing media for Vetiver grass. The results showed that adding *BA bokashi* (a dose of 15 tons/ha) has increased the height and the number of leaves and tillers of vetiver grass. While the addition of *BA bokashi* at a dose of 20 tons/ha was found to have the highest lead absorption level in the soil. Therefore, this study aimed to investigate the valorization of FA combined with blackwater sludge (BWS) as a growing media and its effect on the growth of dwarf elephant grass. The study also explored the potential future application of FABA as a plant media for reclamation of contaminated/ex-mining land with phytoremediation techniques. Better handling of FA and BA may contribute to minimizing or preventing environmental pollution and protecting the surrounding environment.

Research Methods

Materials

FA was obtained from a PLTU in West Java, Indonesia. BWS was collected from a communal domestic waste treatment plant in Tlogomas, Malang City, East Java, Indonesia. Rice straw (RS) was collected from a rice field, while effective microorganism 4 (EM4) was bought from a local agricultural shop in Malang City, East Java, Indonesia. The dwarf elephant grass (*Pennisetum purpureum* cv. Mott) seed was bought from PT. Greenfields Indonesia located in Ngajum District, Malang Regency, East Java, Indonesia.

Composting trials

a. Samples and inoculum preparation

BWS was sun-dried for 3 days to remove excess water content. Rice straw was chopped at a size of 0.5 ± 0.01 cm, aiming to reduce the particle size and thus increase the efficacy of microbial degradation during composting. The sugar solution was prepared at a ratio of 1:1 (sugar:water), and thoroughly mixed until homogeneous. The inoculum for composting was using EM4 solution, prepared and activated with the addition of sugar solution and water, at the following ratio 1:1:100 (EM4:sugar solution:water).

b. Experimental set-up

In this research, a random experimental design was employed with a factor of substrate concentration. This study used three substrates: FA (as the main substrate), SBW, and RS. FA was added with SBW and RS at different concentrations, making a total mixture of 100%, as shown in Table 2. All samples were prepared in triplicate.

c. The composting procedures

The composting procedure followed the method described by Suhartini et al. (2020) and Cholilie et al. (2019) with some modifications. The composting mixture was prepared according to the ratio of substrates added, as explained in Table 2. The mixture was then thoroughly mixed with 0.7% EM4 solution (of the total weight of substrates). The initial moisture content of the mixture for this composting process was set up at 60% with the addition of water. The sample mixture was then incubated at ambient temperature for 21 days. The composting was carried out using a closed plastic container to avoid direct sunlight or to protect from rain. The parameters analyzed include C-organic total, N-total, P-total, K-total, C/N ratio, pH, and MC were carried out on weeks 2 (day 14) and 4 (day 21). These parameters were compared with that of the standard value in SNI 19-7030-2004 (specification for compost from domestic organic waste).

Table 2. Composition of each substrate in the composting mixture

Treatments	Concentration of substrates added (% of total weight)		
	FA	BWS	RS
P1	50	0	50
P2	37.5	25	37.5
P3	25	50	25
P4	12.5	75	12.5

Table 3. Composition of growing media

Treatments	Type of growing media			
	Soil	**FA**	**BA**	**Composted FA (FA:BWS:RS)**
T0	100	-	-	-
T1	75	25	-	-
T2	75	-	25	-
T3	75	-	-	25

Planting trials

a. Preparation and germination of dwarf elephant grass

The dwarf elephant grass seeds were previously rinsed to remove any impurities or residues. Then, the cleaned seeds were soaked in clean water for 24 hours. After that, sunken seeds were selected and planted in soil to germinate for 2 weeks. The germinating seeds, once the root emerges, were carefully selected.

b. Preparation of plant media

The procedure for preparation of the growing media was based on previous research by Hapida (2015). The growing media was prepared in polybags (in triplicate) by mixing all ingredients according to the composition (Table 3). The soil used as a control was obtained from a garden. The compost from the composting of mixture FA:BWS:RS was used based on the best treatment results obtained from the composting trials. These growing media were then used for planting trials.

c. The planting procedure and the experimental set-up

Once the root emerged, the germinating seeds were carefully transplanted into a polybag with the growing media. The watering of dwarf elephant plants was carried out on a daily basis, with the same amount of water given. The dwarf elephant plants were observed every 4 days over 16 days for the following parameters: plant media pH and temperature, ambient temperature, number of leaves, and the height of plants. A completely randomized design was used in this research, with a factor of the composition of plant media prepared in triplicate, as shown in Table 3.

d. The harvesting procedure

The dwarf elephant plants were harvested at the age of 16 days, by taking out the plant, including the root parts. The roots were first'ly cleaned from the soil using clean water and then dried using a towel. The stems and the roots parts were then cut into small pieces for the wet weight measurement. The sample was then dried using oven drying for the dry weight measurement. The plants (i.e. leaves and roots), after the harvesting period, were then analyzed for the Zn absorption ability of the dwarf elephant plants. the Zn concentration was measured for the growing media samples at the initial stage (before) and after the harvesting period.

Analyses and calculation

The moisture content was analyzed using the Gravimetric method (Hawa et al., 2018). The total carbon was measured using the Gravimetric method as explained in ISO 3907:2009 (ISO, 2009). Nitrogen was analyzed using the 4500-N Nitrogen method (i.e. Total Kjedhal Method) (APHA, 2005). The potassium was measured using a flame photometer (Chen et al., 2021). Temperature and pH were analyzed using the standard method of 2310-Acidity, using a pH meter equipped with pH and temperature electrodes (APHA, 2005). The C/N ratio was obtained by dividing the concentration of C by the concentration of N in each sample.

The concentration of Zn was analyzed using atomic absorption spectroscopy (AAS). The ability of dwarf elephant grass to absorption of Zn was then measured as translocation factor (TF), bioconcentration factor (BCF), and enrichment factor (EF). The TF is defined as the ability of the plant to translocate the heavy metals from the root to the shoot parts of the plant, and it is calculated using the formula in Eq.1 (Galal and Shehata, 2015). They further stated that if the TF value is higher than 1, it indicates that the translocation of heavy metals from the root to the shoot (or top part of the plant) has effectively occurred.

$$TF = \frac{Cshoot\ or\ aerial\ part}{Croot} \qquad (1)$$

Where, $C_{\text{shoot or aerial}}$ part is the concentration of heavy metals (or pollutants) in the shoot or aerial part of the plant, and C_{root} is the concentration of heavy metals (or pollutants) in the root.

The BCF is defined as the ability of the plants to accumulate or store the pollutants in the plant's cell tissue, and it is calculated based on the following formula in Eq.2 (Galal and Shehata, 2015; Wu et al., 2018). The plant is categorized as hyperaccumulator species if the BCF value is higher than 1 (Galal and Shehata, 2015).

$$BCF = \frac{C\,root}{Csoil} \quad (2)$$

Where, C_{root} is the concentration of heavy metals (or pollutants) in the root, and C_{soil} is the concentration of heavy metals (or pollutants) in soil or growing media.

The EF represents the phytoremediation ability of plants in adsorbing heavy metals from soils and transporting them to the shoot part of the plants, and is calculated using the formula in Eq. 3. If the EF value is greater than 1, the plants have phytoremediation ability (Galal and Shehata, 2015).

$$EF = \frac{Cshoot}{Csoil} \quad (3)$$

Where, C_{shoot} part is the concentration of heavy metals (or pollutants) in the shoot part of the plant, and C_{soil} is the concentration of heavy metals (or pollutants) in soil or growing media.

Data Analysis

The Analysis of Variance (ANOVA) at a significant level of 5% ($\rho < 0.05$) was carried out using the statistical analysis of RAR software. If the effect of growing media was discovered in treatments, the least significant difference (LSD) test (0.05) was used.

Results and Discussion

Composting of FA with BWS and RS

The characteristics of compost from the composting of FA:BWS:RS mixture at different ratios after 21 days of incubation are shown in Table 4. The table indicates that there was no significant difference between treatment for the parameters of N-total and K. Treatment P1 differed significantly from the other treatments (i.e., P2, P3, and P4) in terms of MC, C/N ratio, and C-total. When compared with the Indonesian Standard for commercial compost made of domestic organic waste (SNI 19-7030-2004), it can be seen that P1 treatment (FA:BWS:RS of 50:0:50) has parameters of MC, C-total, and C/N ratio that exceed the standard values. While P3 treatment (FA:BWS:RS of 25:50:25) has parameters of pH and MC that did not comply with that of the SNI 19-7030-2004. The only parameter of MC in Treatment P4 (FA:BWS:RS of 12.5:75:12.5) that did not meet the standard values. P2 treatment (FA:BWS:RS of 37.5:25:37.5) has all parameters in accordance with the quality of compost in SNI 19-7030-2004.

The results indicate that adding FA at a concentration of 12.5 to 37.5% is possible for producing compost that is suitable as a growing media. This is in accordance with the results reported by Ahmad et al. (2021) that adding FA at a concentration of 40-50% produces a growing media, which unsuitable for enhancing the growth of the pumpkin plant. This finding also indicates that increasing the concentration of BWS from 25% to 75% (of the total mixture weight) did not significantly impact the quality of resulted compost. Thus, based on the comparison with SNI 19-7030-2004, P2 treatment was found to result in a better quality of compost than other treatments, thus it was selected for planting trials.

The Effect of Growing Media on the Dwarf Elephant Grass

a. Temperature and pH of the growing media

Figure 1 shows the trends in temperature and pH of the growing media over 16 days. In general, for both parameters, no significant differences were found from the control and all treatments. The temperature of the growing media was in the range of 24.90 – 27.00, as shown in Figure 1a. Slightly difference in temperature was possibly due to the changes in the weather conditions during the observation period, which may affect the length of the sunlight emitted to the plant and the growing media. As previously stated by Gungor and Yildirim (2013) and Jozay et al. (2020) that various environmental factors (such as length of sunlight, the water content in soil, mineral nutrients present in soils, temperature, etc.) may affect the plant's growth.

Figure 1b shows that the pH of the growing media was in the range of 6.90-7.70 from day 4 to day 16. On day 16, however, the pH of all growing media is close to neutral. The value may influence the microbial activity and the degradation of organic matter in the soil (Kelly et al., 2014). Furthermore, a good quality growing media should have a pH value close to neutral because the nutrients become more soluble and are easily absorbed by the plants (Prasad et al., 2020). Similarly, Penn and Camberato (2019) also stated that the pH mainly affects the plant's ability to control nutrient availability. The results in this study indicate that the growing media has a pH value suitable for growing the dwarf elephant grass. According to Sirait (2017), the dwarf elephant grass is a plant with a high tolerance and can adapt to the growing media with a pH in the range of 4.5 to 8.2.

Table 4. The characteristics of compost after 21 incubation from all treatments samples (in average values)

Parameters	Unit	Treatments				SNI 19-7030-2004	
		P1	P2	P3	P4	Min.	Max.
pH		7.37±0.26 ^{b}	7.10±0.16 ^{b}	6.63±0.12 ^{a}	7.17±0.21 ^{b}	6.80	7.49
MC	%	74.24±4.03 ^{c}	47.11±3.71 ^{a}	56.66±0.54 ^{b}	54.70±5.16 ^{b}	-	50.00
C-total	%	35.54±5.13 ^{b}	17.26±3.76 ^{a}	23.51±2.01 ^{a}	20.02±1.45 ^{a}	9.80	32.00
N-total	%	1.07±0.05 ^{a}	1.63±0.56 ^{a}	1.74±0.20 ^{a}	1.41±0.17 ^{a}	0.40	-
P (P_2O_5)	%	0.38±0.05 ^{a}	0.49±0.20 ^{a}	0.60±0.04 ^{a}	1.22±0.35^{a}	0.10	-
K (K_2O)	%	1.72±0.04^{a}	1.80±0.21 ^{a}	1.87±0.18 ^{a}	1.88±0.08 ^{a}	0.20	-
C/N ratio		33.29±3.95 ^{c}	13.80±3.92 ^{a}	13.84±0.18 ^{a}	13.86±0.56 ^{a}	10.00	20.00

Notes: C-total, N-total, P-total and K-total were measured on a dry basis. The alphabetic letter (a-c) indicates significant different among treatment in each parameter ($\rho<0.05$). ± indicates standard errors from three measurements

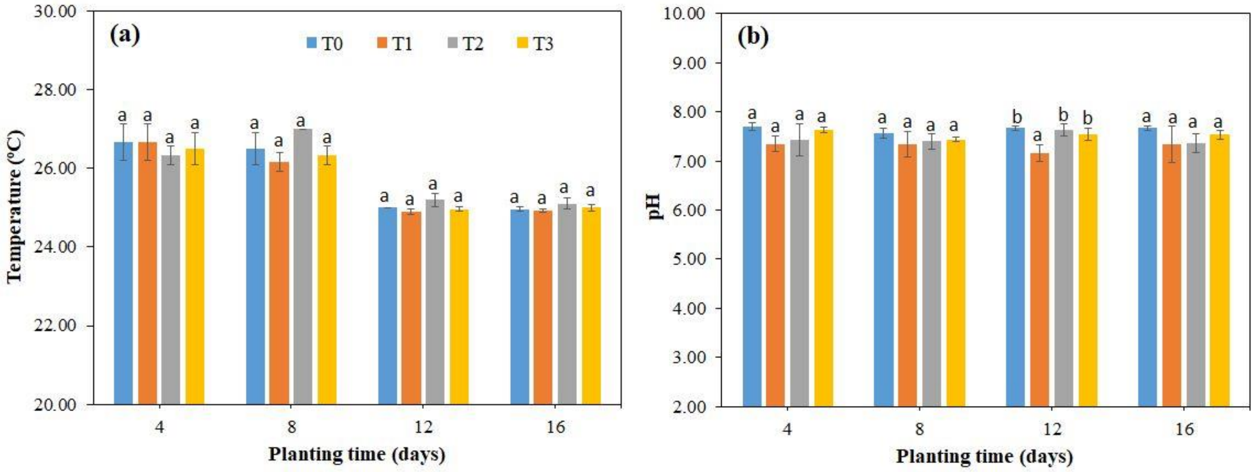

Figure 1. Trends in temperature (a) and pH (b) of the plant media over 16 days planting period. Error bars represents standard deviation of three measurements

b. *Effect of the growing media on the plant's growth characteristics*

Figure 2 shows that there was an increase in the number and length of leaves of dwarf elephant grass from all treatments from day 4 to day 16. After 16 days of the planting period, compared to the control treatment (T0), the number of leaves of dwarf elephant grass from the addition of FA (T1) and composted FA (T3) gave similar results with an average value of 10.67. As shown in Figure 2a, the T2 treatment resulted in a slightly lower number of leaves (10.33). However, it was not a statistically significant difference compared to other treatments. Figure 2b also shows a similar trend, but T3 performs similarly the control treatment (T0). The T1 and T2 treatments slightly decreased the length of leaves, with a value of 48.06 cm and 45.89 cm, respectively. However, they were not statistically different compared from the control (T0) and T3 treatments. According to Riaz et al. (2015), an increase in the number or size of leaves indicates nutrient availability in the growing media and the adaptability of dwarf elephant grass to the growing media. Therefore, according to the number and length of leaves, the addition of composted FA (T3) could be considered to provide better nutrients in the growing media, followed by the addition of FA alone (T1) and BA alone (T2).

Figure 3 illustrates the effect of growing media on the dry weight and fresh to dry weight of dwarf elephant grass after a 16-day planting period. Figure 3a shows that using T3 growing media showed the highest increase in dry weight of root, giving an average improvement of 16%.This was followed by the addition of FA treatment (T1) with a 3% improvement compared with the control (T0) treatment. Ahmad et al. (2021) reported that the addition of FA to the soil at a dose of 10–30% significantly affects the growth of pumpkin crops (Cucurbita moschata), as indicated by an increase in plant fresh and dry biomass. Kumar and Kumar (2021) also reported that the addition of FA at a concentration of 25 g/m^2 to the soil significantly improves the soil's physical and chemical structures. As a result, FA acts to provide additional micro- and macronutrients required by plants to grow.

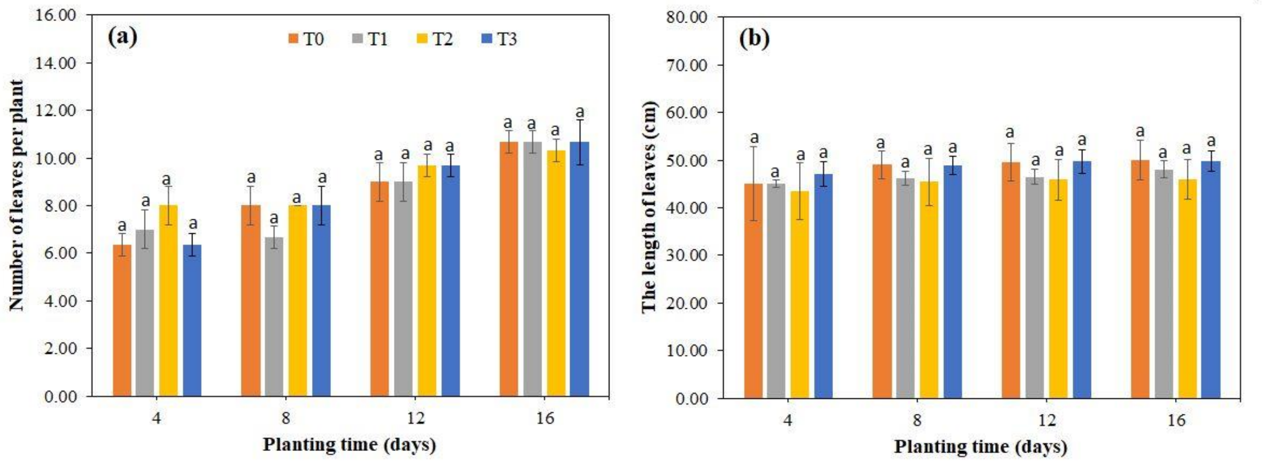

Figure 2. Effect of different growing media on number of leaves (a) and the length of leaves (b) of dwarf elephant grass over 16 day planting period. Error bars represents standard deviation of three measurements

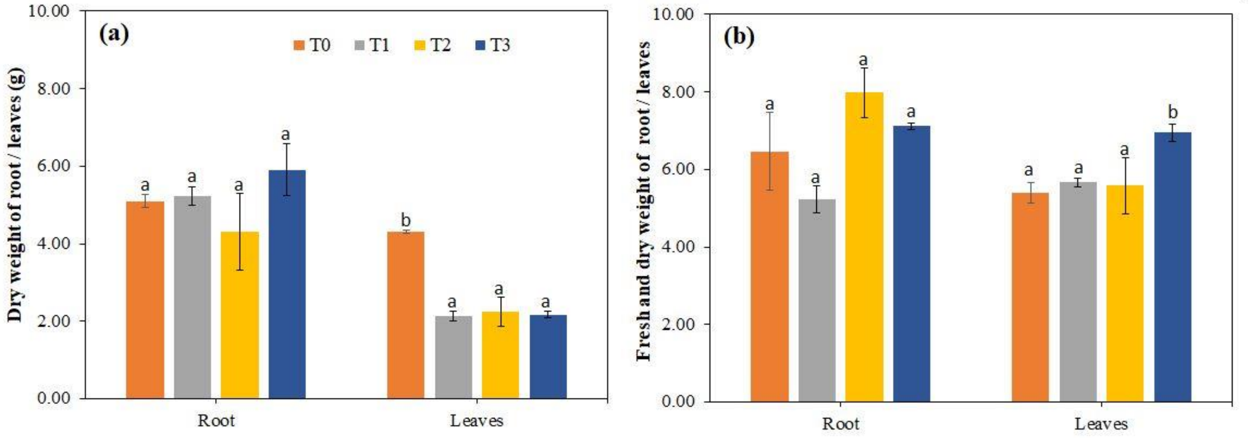

Figure 3. Effect of different growing media on dry weight of root or leaves (a), fresh to dry weight ratio of root or leaves (b) of dwarf elephant grass over 16 day planting period. Error bars represents standard deviation of three measurements

The study showed an increase in the yield of cowpea (Vigna unguiculata L.) crops after the addition of FA to the soil. The lowest dry weight of root was found in the T2 treatment (addition of BA), with a 15% decrease compared to control (T0). The T1 treatment was significantly different from other treatments. However, the dry weight of leaves from treatments T1, T2, and T3 were statistically different and significantly lower than the control (T0), with approximately a 50% reduction.

As can be seen in Figure 3b, it indicates that T2 has the highest fresh to dry weight ratio of root, with a value of 23% greater than that of the control (T0) treatment. This was followed by T3 treatment with a 10% improvement. While the lowest fresh to dry weight ratio was found in T1 treatment, with a 19% decrease in weight compared to control. T1 treatment was significantly different from T2 and T3 treatments. For the leaves part, compared to control (T0) treatments, T3 gave the highest increase in the fresh to dry weight ratio, with an average improvement of 29% (see Figure 3b). Other treatments of T1 and T2 also showed a slight increase, with values of 5% and 6%, respectively. These treatments were not significantly different statistically compared to the control treatment. The T3 treatment was significantly different from the control (T0) treatment in the fresh to dry weight ratio of leaves.

As shown in Table 5, after 16 days of the planting period, no significant difference was found in the number and length of leaves, the dry weight of the root, as well as the fresh to dry weight ratio of the root. This indicated that adding FA, BA, and composted FA at a concentration of 25% was acceptable to be used as growing media.

Table 5. Effect of growing media on number and length of leaves, dry weight of root and leaves, and fresh to dry weight of root and leaves of dwarf elephant grass after harvesting at day 16

Treatments	Number of leaves (cm)	Length of leaves (cm)	Dry weight (g)		Fresh to dry weight ratio	
			Root	Leaves	Root	Leaves
T0	10.67±0.47^{a}	49.95±4.14^{a}	5.09±0.16^{a}	4.32±0.05^{b}	6.47±1.01^{a}	5.40±0.26^{a}
T1	10.67±0.47^{a}	48.06±1.80^{a}	5.23±0.25^{a}	2.14±0.12^{a}	5.24±0.35^{a}	5.66±0.11^{a}
T2	10.33±0.47^{a}	45.89±4.21^{a}	4.31±0.08^{a}	2.25±0.37^{a}	7.98±0.64^{a}	5.58±0.72^{a}
T3	10.67±0.94^{a}	49.78±2.08^{a}	5.91±0.68^{a}	2.17±0.09^{a}	7.12±0.09^{a}	6.95±0.23^{b}

Notes: The alphabetic letter (a-b) indicates significant different among treatment in each parameter ($\rho<0.05$). ± indicates standard errors from three measurements

Table 6. Characteristics of biomass root, leaves, TF, BCF, and Zn concentration after harvesting at day 16

Treatments	Zn Concentration (ppm)			Biomass (g)		TF	BCF	EF
	Growing media	Root	Leaves	Root	Leaves			
T0	149.10±2.786^{a}	214.13±9.06^{a}	112.77±4.87^{b}	13.13±1.36^{a}	12.90±0.63^{c}	0.53±0.02^{c}	0.70±0.02^{b}	0.76±0.03^{c}
T1	134.10±11.18^{a}	273.53±0.90^{b}	78.73±1.55^{a}	15.12±3.16^{a}	6.64±0.37^{a}	0.29±0.01^{a}	0.49±0.04^{a}	0.59±0.05^{b}
T2	179.73±4.96^{b}	209.53±7.39^{a}	285.47±10.01^{c}	13.64±3.61^{a}	6.76±0.87^{a}	1.37±0.09^{d}	0.86±0.05^{b}	1.59±0.02^{d}
T3	243.33±3.49^{c}	301.80±7.73^{c}	120.93±1.75^{b}	21.84±2.08^{b}	8.15±0.31^{b}	0.40±0.01^{b}	0.81±0.02^{b}	0.50±0.01^{a}

Notes: The alphabetic letter (a-d) indicates significant different among treatment in each parameter ($\rho<0.05$). ± indicates standard errors from three measurements

This study is in accordance with previous studies reported by Ahmad et al. (2021) and Kumar and Kumar (2021) that the addition of FA as a component in the growing media is possible as it has a positive effect on the plant's growth. Similarly, Sormunen et al. (2016) also found that BA is potentially added as a component in growing media. However, in general, T3 treatment (i.e. addition of composted FA) improves in the growth of dwarf elephant grass more than the control treatment. This is in line with a previous study by Ram and Masto (2014), who stated that blending FA with other materials as growing media resulted in a better performance compared to that of FA alone, possibly due to their synergetic interaction. The synergetic interaction is also known as co-metabolism (Gu, 2016). The co-metabolism due to the co-addition of FA, BA, or other substrates could contribute to enhancing the availability of nutrients, improving the soils chemical and physical properties, promoting better microbial stimulation, providing additional organic matter required by the plants, reducing the bioavailability of toxic metals, as well as improving pH buffering (Gu, 2016; Ram and Masto, 2014). Mupambwa and Mnkeni (2018) also highlighted that adding FA could enhance the nutrient mineralization and the efficacy of the vermicomposting process, leading to significant improvement in the compost's quality as an organic fertilizer or nutrient source in agriculture.

The Efficacy of Zn Absorption by the Dwarf Elephant Grass

In terms of Zn concentration, the results showed that the T3 treatment has the highest Zn concentration accumulated in the root of dwarf elephant grass, followed by the T1 treatment. Both treatments differ significantly from T0 and T2 treatments. While the Zn concentration in leaves, T2 was found to have the highest value at 285.47 ppm. The lowest was the T1 treatment, with a value of 78.73 ppm. This treatment was significantly different compared to other treatments and the control. Again, the T3 treatment was observed to have the highest concentration of Zn in growing media, about 1.63-fold of the control value, and statistically different from the control (T0). This was followed by the T2 treatment, which had a 1.2-fold higher Zn concentration in the growing media than the T0 treatment and was statistically different from each other. The lowest Zn concentration in growing media was found from T1 treatment and was not significantly different from the control (T0).

Table 6 also shows that the highest biomass value in root was found in the T3 treatment (21.84 g), which was significantly different from that of the control treatment (T0). While T1 and T2 treatments were observed with no significant difference from the control. The highest biomass value in leaves resulted from the control (T0) at a value of 12.95 g, which was statistically different from other treatments. This was followed by T3 treatment at a value of 8.15 g, which significantly different from T1 and T2 treatments. The T1 treatment produced the least amount of biomass in the leaves, with no statistically significant difference from the T2 treatment. The results, however, indicate that different growing media have no significant effect on improving the weight of biomass leaves compared with the control (T0). This could potentially be due to a slight difference in the pH of the growing media. As stated by Riaz et al. (2015), besides nutrients' composition, nutrient form, and organic compounds present in the growing media, pH may also have an impact on the nutrient accessibility by plants. Hence, changes in pH (i.e. decrease or increase) influence the plant's growth and development, as it damages the root or decreases the nutrient availability.

The highest TF and EF values resulted from T2 treatment, giving the values of 1.37 and 1.59, respectively, as shown in Table 6. This indicates that translocation of Zn in the cell tissue of dwarf elephant grass or to the aerial part of the plants occurred effectively, as previously stated by Galal and Shehata (2015). This was followed by the control (T0) and T3 treatments. In terms of BCF, it shows that T2 and T3 gave better efficacy than T1 and T0. T1 treatment showed the lowest TF and BCF parameter values, while T3 treatment yielded the highest EF parameter. According to the findings, the dwarf elephant grass was able to translocate zinc into its roots and aerial portions (i.e. leaves). As previously indicated in various research, the plant has the potential to be used as a phytoremediation plant in heavy metal-contaminated or ex-mining terrain (Kowitwiwat and Sampanpanish, 2020; Tananonchai and Sampanpanish, 2020). Due to its cost-effectiveness, capacity to grow quicker in any environment, and ability to immobilize heavy metals, grass plants are viewed as a sustainable land restoration option. The quality of heavy metal-contaminated and ex-mining areas, as well as the surrounding ecosystem, should be enhanced and restored by employing grass plants.

Estimation of Future Application for FA and BA - Reclamation of Contaminated/Ex-mining Land

Several studies have highlighted the use of FA and BA for the reclamation of mine backfill (Guo and Wu, 2018; Kim et al., 2017; Skousen et al., 2012). Furthermore, Gajić et al. (2018) and Kostić et al. (2018) stated that applying FA and BA to ex-mining land could improve the soil quality physically, chemically, and biologically, thus providing better nutrients and conditions for plant growth. This is because FA contains CaO and MgO, which have neutralizing power on the soil (Jambhulkar et al., 2018; Ram and Masto, 2014). Several other benefits of the application of FA and BA are improving soil texture, percolation, aeration, and water retention in the treated soil zone (Weber et al., 2015). In addition, FA and BA can reduce soil bulk density and the consumption of other soil amelioration materials, which can reduce mobility and absorb metals contained in the soil due to its alkaline nature (Shaheen et al., 2014). FA and BA can also be used for land revegetation, taking into account several important aspects, such as the selection of plant species, improvement of appropriate biotechnology (Rhizobium and mycorrhizal species), and improvement of organic content (soil cover) used (Maiti and Prasad, 2016; Weber et al., 2015). Although plant growth in FA has some limitations, the agronomic potential of FA is significantly high. This is evidenced by the success of increasing plant growth through improving soil properties using FA (Kostić et al., 2018). In addition, the use of the phytoremediation approach is a promising alternative for dealing with heavy metal contaminated soils because the technology is sustainable and economically feasible (Belouchrani et al., 2016).

Based on the results of the investigated study, the potential future application of FA and BA combined with domestic waste (i.e. blackwater and greywater) for reclamation of contaminated/ex-mining land with an integrated biorefinery approach is illustrated in Figure 4. Within this proposed concept, the combination of FA and BA, blackwater, and greywater functioned as a plant media for non-food phytoremediation plants (i.e. grass). The harvested grass can be further composted for producing commercial-quality compost to be used either in the agricultural or forestry sectors.

Based on the figure, the proposed work is composed of several stages as follows:

a. The composting of FA/BA and blackwater (as growing media)

In this case, FA and BA are used as material to replenish (fill or cover) the ex-mining soil because of their low permeability, thus it can prevent chemical leaching (Roy, 2021). FA and BA are alkaline, have good water holding capacity, and are good soil enhancers, thus can initiate the process of plant growth (greening of land) (Shaheen et al., 2014; Weber et al., 2015). Usmani et al. (2019) and Mandpe et al. (2021) stated that composting is a necessary step prior to the application of FA to the soil, which aims to reduce the contaminants and enhance the quality of FA. Furthermore, as explained above, previous researchers also suggested mixing FA or BA with organic or animal waste to increase plant growth. Oncioiu et al. (2018) also found that the concurrent use of FA with cow dung can increase crop production by 36.5%. Panda and Biswal (2018) found that the use of FA combined with soil and cow dung at a ratio of 20:70:10 (%) can increase vegetable productivity, and at a ratio of 15:70:15 (%) flower productivity also increases. It can be concluded from these studies that the addition of organic waste/manure in FA can provide additional organic carbon. Thus, it can improve the soil's physical properties and increase crop production. Therefore, prior to application to heavy metal-contaminated or ex-mining land, FA and BA should be mixed by adding blackwater. This process aims to increase the nutrient content, so it can be used either as fertilizer or plant media. By doing this, various types of waste can be tackled, including reducing the amount of FA, BA, and blackwater.

b. Greywater as liquid fertilizer for grassland

Furthermore, greywater may also be added to the FA: BA: blackwater mixture with a certain ratio. In this case, greywater is used as an addition to natural liquid fertilizer through an irrigation mechanism due to its relatively high organic matter content, as explained previously. The results from Panda and Biswal (2018) also showed that the application of FA and cow dung combined with irrigation using a mixture of clean water:greywater (75:25 (%) and 50:50 (%)) increased the vegetable crop production. While the use of mixed irrigation of clean water: greywater at a ratio of 50:50 (%) has resulted a higher productivity of rice plants compared to that of using the ratio of 100:0; 75:25 and 0:100 (%). Kafil et al. (2019) also reported that using domestic or industrial wastewater has significant potential as a source of irrigation water on heavy metal contaminated soil. Their results showed an increase in the productivity of grass plant biomass. Furthermore, Paulo et al. (2013) conducted research on blackwater and greywater treatment using an evapotranspiration tank (with a depth of 1 m and a layer of gravel, sand, and soil), with several types of plants such as banana plants (*Musa cavendishii*), Taioba (*Xanthosoma sagittifolium*) and berry plants (*Canna* sp.). The results showed that with this method, all plants could grow well and the pollutants could be reduced. Thus, allowing the reuse of greywater and the presence of nutrients in blackwater as a growing media.

Therefore, in this proposed scenario, the addition of greywater is critically important to increase the efficacy of the reclamation process. Such measures contribute to reducing pollution and the contaminants in the environment, as well as reducing the amount of potential wastewater generated from greywater.

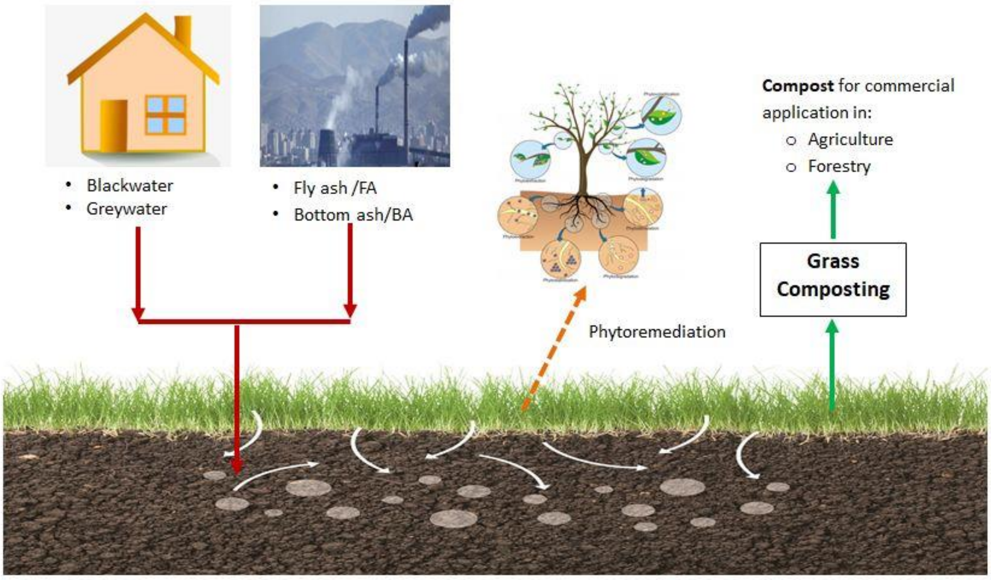

Figure 4. Schematic of potential future application of FA and BA for sustainable reclamation of contaminated/ex-mining land with integration of biorefinery approach

c. Cultivation of grass plants

Several factors affect the growth of plants grown on FA and BA, including chemical, physical, and biological factors (Jambhulkar et al., 2018). Chemical factors include high initial pH and dissolved salt concentration, levels of phytotoxic B and several other elements, as well as nutritional deficiencies such as N and P. Physical factors include the occurrence of natural compaction of fine ash particles and the formation of a dense cement layer of ash due to its pozzolanic properties. Biological factors include microbial activity, low nutrient turnover, and a lack of symbiotic inoculums (e.g. Rhizobium and mycorrhizae). In addition, other factors to be considered during the phytoremediation process include soil moisture (adequacy irrigation if needed), soil tillage (including soil type, frequency, and seasonality), additional organic materials (i.e. manure sludge, compost, vermicomposting fertilizer, and shredded plant residues), as well as fertilization with synthetic fertilizers (i.e. urea, N, P, and K) (Ashraf et al., 2019; Dhanwal et al., 2017; Pandey and Bajpai, 2019). Based on the review above, grass plants are one of the best options. Apart from being not a food crop, the grass is a plant that is easy to grow and takes a relatively short time to harvest. Srivastava et al. (2014) stated that grass plants such as *Vetiveria zizanoides* and *Cymbopogan flexuosus* improved the physicochemical characteristics of mining areas (mine spoil). Furthermore, they found that the combination of photosynthetic activity and leaf area of grass plants can protect the soil from erosion and water runoff.

Therefore, in this proposed scenario, grass plants are selected to be grown on the plant media composed of FA:BA:blackwater with irrigation of greywater. Grass, in addition to being able to use nutrients in plant media, can also act as a phytoremediation plant, removing harmful minerals from ex-mining soil (Banerjee et al., 2019). Ko et al. (2017) reported that Napier grass could grow well on metals-contaminated soils and have high phytoremediation ability by adsorbing high concentrations of Zn, Cd, and Cr. They added that the harvested Napier grass had the potential to be used as feedstock for bioethanol production without any inhibition observed due to adsorbed heavy metals.

Furthermore, Haq et al. (2020) stated that using grass for phytoremediation of heavy metals contaminated soils is one of the sustainable approaches, as grass plants have high biomass yield within short periods of cultivation, have a high tolerance to drought conditions or temperature changes, as well as have the high metal-tolerant ability. Gravand et al. (2021) also reported that revegetating heavy metals contaminated soil using vetiver grass is recommended because it has high efficacy in removing pollutants, and is more cost-effective and ecologically beneficial. In addition, several studies have also highlighted that grass plants have great potential as phytoremediation plants for FA or mining or contaminated agricultural soil (Ghosh et al., 2015; Kisku et al., 2018; Maiti and Prasad, 2016). Roy (2021) added that using grass plants for cover crops (phytocover) on ex-mining soil that has been remedied with the addition of FA is the most efficient strategy because grass plants can grow easily and can form plant vegetation in a short time. Therefore, in this proposed scenario, using grass plants can also increase soil fertility (due to the use of FA, BA, blackwater, and greywater), prevent erosion, reduce air pollutant emissions, and absorb heavy metals.

d. Valorization of grass plants for high-value added products (i.e. compost)

The harvested grass plants are renewable and sustainable plant biomass sources, potentially for further valorization into high economic value-added products using an integrated biorefinery concept approach. Sotenko et al. (2017) stated that combining phytoremediation and biorefinery is a very effective approach to removing heavy metal contamination in soil and utilizing biomass. Therefore, in this proposed scenario, the harvested grass plants could be used as raw material for composting using aerobic composting technology. Composting technology is considered an appropriate option. Singh and Kalamdhad (2018) stated that composting technology is highly efficient for stabilizing and immobilizing of heavy metals, where the metal fraction becomes more stable during the compost maturation process. A recent study by Yoshii et al. (2019) found that the composting of grass plant silage contaminated with nuclear material can produce compost products that are safe to be applied as organic fertilizer on vegetable crops (such as tomatoes, soybeans, carrots, etc.). In this proposed scenario, to enhance the efficacy of the composting process, the grass plants are mixed with other organic waste that is locally abundant. The mixing aims to obtain ideal composting conditions such as C/N ratio (30), water content (60%), and neutral pH

(~7). At this stage, testing on the quality of compost from grass plants (such as heavy metal content and pathogenic bacteria) could be conducted to evaluate the feasibility of applying compost to other plants. The resulting compost's quality should also comply with the safe application to the environment and human health.

e. Compost application for wood production forest and agricultural land

Research by Järvis et al. (2016) found that the application of compost to several species of woody plants (such as *Alnus incana* L. Moench, *Alnus glutinosa* L. Gaertn, Betula pendula Roth, and *Populus tremula* L.) was able to increase tree height and growth. Tong et al. (2018) also stated that applying compost to *Sophora japonica* Linn. in the forest in the city of Beijing was able to improve soil conditions, microorganisms in the soil and plant growth. As a result, the compost from grass grown on ex-mining polluted land is applied to woody plants in wood production forests or the agricultural sector in this proposed scenario. However, a more thorough assessment of the influence on soil quality, plant growth, and the impact on the surrounding environment is required.

Policies and Regulation Consideration

In applying this proposed scenario, the policy or regulatory aspect becomes one of the essential aspects to be considered. The Indonesian Government Regulation (PP) No. 85 of 1999 (Improvement of PP No. 18 of 1999) and PP No. 101 of 2014 stated that FA and BA are included in the category of toxic and hazardous waste (known as B3 waste) because of the content of heavy metals and organic matter PNA (polynuclear aromatics) (The Ministry of State Secretariat Republic of Indonesia, 2014). However, these regulations have been replaced by the newest regulation (PP No. 22 of 2021) about the Implementation of Protection and Management of the Environment (The Ministry of State Secretariat Republic of Indonesia, 2021). This regulation stated that FA and BA are no longer categorized as B3 waste and emphasized more on their sustainable valorization for high-value added products. With this new regulation, the valorization of FA and BA should be focused on the feasibility evaluation of product type, product quality, referenced standard, and target beneficiary. Furthermore, the sustainable valorization of FA and BA should include a statement of changes in the environmental permit documents. In addition, with this new regulation, transportation and beneficiaries partners do not need a licensed party related to B3 waste, but they are required to have documented the amount and the person in charge either in an offline or online reporting system (i.e. SIRAJA LIMBAH in https://plb3.menlhk.go.id/siraja-limbah-2020/login/index/app/siraja).

FA has several classifications, namely FA class F (if CaO content is < 10%) and class C (if CaO content > 10%) (Assi et al., 2020; Jambhulkar et al., 2018). This causes the potential for FA and BA applications to be limited, and the waste utilization and applications must comply with regulations and standards. According to Silva et al. (2019), the rules or guidelines for using FA and BA on agricultural land and forests are still very limited, because these wastes are not listed as a secondary material to be applied as fertilizer directly. Especially in Indonesia, PP No. 101 of 2014 article 54 stipulates several potential uses for FA and BA, such as a source of raw materials (such as cement additives) and energy sources. However, the utilization must consider the availability of technology, product standards, and environmental quality standards. Thus, using FA, BA, blackwater, and greywater as growing media or compost should comply with the quality standards that are safe for the environment and human health. A further in-depth investigation is critical.

Conclusion

The findings in this study demonstrated that composting of FA with the addition of BWS and RS is potential and resulted in good quality compost that meets the SNI standard for compost from waste. The application of FA, BA, and composted FA as growing media has a different effect on the plant's growth and development. The addition of a composted FA as a component in the growing media provided a better improvement in the growth characteristics of the dwarf elephant grass, than adding FA and BA alone. However, the addition of BA as growing media produced the highest TF, BCF, and EF values, indicating that the dwarf elephant grass has a great ability to adsorb heavy metals, such as Zn. Therefore, it can be concluded that FA, BA, and composted BA could potentially be used as an additional ingredient in the growing media. These methods can be used to reclamation heavy metal-contaminated or ex-mining areas, which may reduce the potential risk of heavy metals re-entering the food chain and the surrounding environment. Furthermore, direct application of FA and BA (combined with blackwater and greywater) as growing media of dwarf elephant grass can be an alternative for a sustainable valorization route. Biorefining opportunities from the proposed scenario may provide additional economic and environmental benefits for relevant stakeholders such as mining industries or coal-based energy plants.

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Declarations

Conflict of interests The authors declare no competing interests.

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