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Phaselous vulgaris Growth under the Influence of Manufactured Coal Ash Aggregates

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A B S T R A C T

Manufactured coal ash aggregates (MAs) are a 2:1 (w/w) solidified composite of fly and bottom ash. The current study assessed the feasibility of beneficial utilization of MAs as a subsoil substitute for open-pit restoration to phyto-viable land. A series of indoor and outdoor experiments examined *Phaselous vulgaris* growth under the influence of MAs in the soil environment. With the MAs layer below the topsoil, *P. vulgaris* showed enhanced growth with respect to shoot height, leaf number, and leaf chlorophyll intensity. Similar growth enhancement was observed when the MAs were mixed with topsoil or applied as a micronutrient source over the topsoil. Thus, MAs are beneficial as a subsoil substitute for open-pit restoration to phyto-viable land, reducing exploitation of natural soil resources and enhancing plant growth.

A R T I C L E   I N F O

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Keywords: Manufactured coal ash aggregates; *Phaselous vulgaris*; restoration

1. Introduction

As the magnitude of civil, transportation, and construction infrastructure has expanded since the industrial revolution, demands for construction-grade sand and gravel have subsequently increased. These construction raw materials are being exploited around the world and many excavated sites, including open-pit quarries, need to be appropriately managed. These sites potentially represent risks to health and safety of people and stock due to dangerous vertical pit walls or water accumulation. Restoration of such sites is typically done by backfilling the residual soils on site and, if not enough, additional soils are excavated off site and transported to the site. The latter can be costly due to excavation and transportation, and degrades natural soil resources.

A number of studies have been conducted to evaluate the effects of coal combustion byproducts (CCPs) application on growth of plants and crop production (Jala and Goyal, 2006). Fly ash (FA) is the most frequently tested CCP for its beneficial utilization, followed by bottom ash (BA) (Pandey and Singh, 2010). It should be noted, however, that the effects of CCPs on plant growth and crop production largely depend on the physiochemical properties of CCPs and soils.

Reported benefits of CCPs (mainly, FA) application include (1) increase in water holding capacity that could decrease irrigation frequency and subsequently increase water savings (Belyaeva and Haynes, 2009; Pandey et al., 2009), (2) reduction of soil acidity-related constraints (Pandey and Singh, 2010), and (3) provision of essential micronutrients for plant growth and development (Jala and Goyal, 2006). Negative aspects of agricultural CCP application include (1) excessive trace element loadings that may increase food chain metals (Peralta-Videa et al., 2009), (2) high soluble salt loadings that may reduce initial plant growth (Palumbo et al., 2004), and (3) toxic substance leaching into the groundwater (Singh and Paul, 2001).

Manufactured coal ash aggregates (MAs) are a 2:1 (w/w) solidified composite of FA and BA that are mixed in water and then air-dried. They gain strength with time due to cementitious reactions. MAs can have better engineering properties than either FA or BA since they are structurally stronger and more chemically stable (Pando and Hwang, 2006). Recently, MAs were documented for their sorptive capacity of aqueous trinitrotoluene (Hwang and

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Table 1
Characteristics of top soil used (± standard deviation, n=3)

Characteristics	Unit	Value
pH	Unitless	6.5 ± 0.1
Soil organic matter	%	5.69 ± 0.17
Total nitrogen	mg/g as N	0.20 ± 0.01
Total phosphorus	mg/g as P	0.04 ± 0.01
Total heterotrophic bacteria	CFU/100 mL	6×10^6
Soil dehydrogenase activity	μg TPF/100 mL	1428 ± 403
Soil texture classification	Loamy sand (Sand 75.1 ± 2.0%; Silt 13.3 ± 0.2%; Clay 11.6 ± 2.1%)	

Hernandez, 2010). The current study was conducted to assess the feasibility of beneficial MAs utilization s as a subsoil substitute for open pit restoration to phyto-viable land. A series of indoor and outdoor experiments assessed *Phaselous vulgaris* (common bean) growth under the influence of MAs in soil environments.

2. Materials and Methods

2.1 Plant, soil, and MAs

Phaselous vulgaris seeds were selected for their fast growing characteristics and convenient size for lab-scale experiments. In addition, *P. vulgaris* has widely been utilized for assessment of metal-induced oxidative stress in soils (Van Assche and Clijsters, 1990), heavy metal phytoaccumulation (Theodoratos et al., 2002), and heavy metal phytoavailability (Meers et al., 2007).

An organic-rich soil from a local area (Santa Isabel, Puerto Rico) was used as a topsoil for the experiments. Soil characteristics are shown in Table 1. After being transported to the laboratory, the soil was dried at 105 °C for 24 h, and then sieved to collect soil particles smaller than 2.0 mm.

MAs were collected from a local coal-burning power plant (AES Puerto Rico) located in Guayama, Puerto Rico. The plant combusts coals in a circulating fluidized bed. Selective non-catalytic reaction, circulating dry scrubber with limestone, and electrostatic precipitator are used for reductions of nitrogen oxides, sulfur dioxide, and particulate matter, respectively, in flue gas emission. The main MAs chemical components were 51% (w/w) mixture (silica, alumina, and ferric oxides), 30% (w/w) lime, and 15% (w/w) sulfur trioxide (Fig. 1). According to the American Society for Testing and Materials (ASTM) (ASTM Standard C 618), FA can be classified in two main types: Class C and Class F. Although the ASTM classification of FA is not applicable to MAs that are a solidified composite of FA and BA, MAs can be regarded as a Class C-type CCP based on the chemical properties. However, the sulfur trioxide concentration of 14% in MAs exceeds the maximum concentration of 5% for a Class C- or F-type FA. Prior to use, they were crushed mechanically and sieved to collect the particles sizes ranging from 2.36 to 9.53 mm.

2.2 Preparation of the plant pots

MAs can be utilized either separately from the top soils or after being mixed with the top soils. For a separate application, MAs can be put either below or above the top soils. Therefore, three different MA application scenarios were tested in the current study: MAs layer as subsoil substitute, MA mixed with the top soil, and topical MA application on the soil. The following sections explain each scenario in detail.

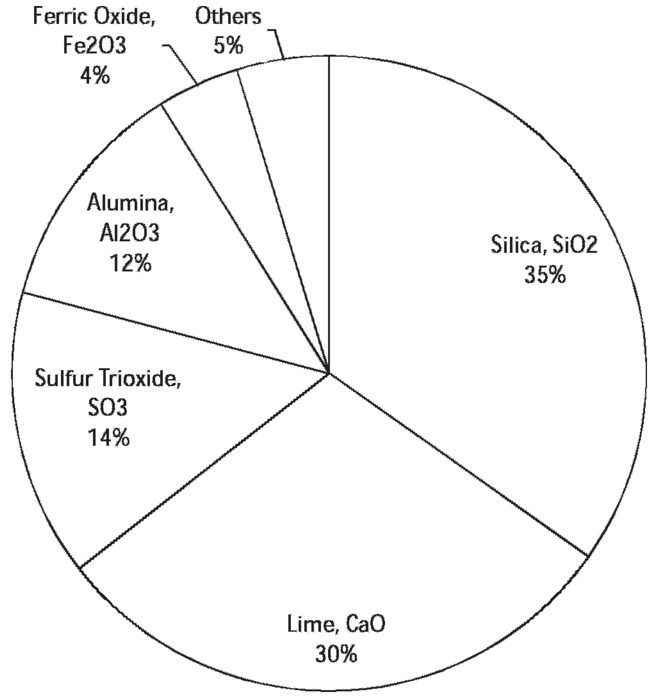

Fig. 1. Metal oxide composition of the MAs (%, wt).

2.2.1 MAs layer as subsoil substitute

To assess the feasibility of MAs utilization as a subsoil substitute, MAs were applied in a layered mode below the topsoil. Plant pots were made of 33- × 20- × 20-cm acrylic plates. The topsoil and MAs were placed at a bulk density of 1.47 ± 0.16 (n = 4) and 0.86 ± 0.08 g/cm^3 (n = 2), respectively. As shown in Table 2, the control pot (1) had only 20 cm of topsoil. In two additional pots (2 and 3), MAs were layered at a depth of 15 or 10 cm. This corresponded to higher application rates of 800 and 400 tons MA/ha for the pots 2 and 3, respectively, than those of FAs found in the literatures. For an example, Ram et al. (2006) tried one-time and repeat applications of lignite fly ash (LFA) from 5 to 20 tons/ha and found an increased crop yield (grain and straw) by 3.0 to 42.0%, with the repeat LFA applications of 20 tons/ha producing the maximum yield. For another example, Yunusa et al (2006) reported an increase of the early growth of canola with an FA application of 25 tons/ha to loamy sand and no further growth benefit with higher FA application rates. They also found that seed yield did not decrease for the plants grown at even 625 tons/ha.

Gravel was layered in a fourth pot in the same manner as the MAs were in pot 3. Pot 4 was run in comparison to pot 3 to assess the potential physical interference of the MAs, which had similar physical characteristics to the gravel used.

Each pot had six *P. vulgaris* seeds sown at a depth of 3.8 cm. Plants were grown with a 9 h/d light source (GRO-LUX, Sylvania-20 W). 640 mL of tap water was evenly sprayed to the pots three times a week. The volume of water application was calculated according to the local precipitation data. Shoot height, leaf number, and days until the first cotyledon emergence were monitored during the 38-d experiment.

2.2.2 MAs mixed with the topsoil

An additional indoor experiment assessed the direct influence of MAs on *P. vulgaris* growth by 1:1 or 2:1 (w/w) mixing of MAs with the topsoil. A control system was also run with 100% topsoil.

Table 2
Depth profile of the indoor pots with the MA layers below the top soil

Depth (cm)	Pot 1	Pot 2	Pot 3	Pot 4
0–10	TS	TS	TS	TS
11–15	TS	TS	MA	GR
16–20	TS	MA	GR	GR

Note) TS: top soil, MA: manufactured coal ash aggregates, GR: gravel

6.4 cm (ID) × 15.2 cm (H) pots were packed with the mixed MAs and topsoil and each pot was sown with four *P. vulgaris* seeds at a depth of 3.8 cm. The MA application rate was calculated to be 400 and 800 tons/hectare for the pots of 1:1 and 2:1 (w/w) mixing, respectively. 40 mL of tap water was sprayed to the pots three times a week. Plants were grown under a light source (GRO-LUX, Sylvania-20 W) for 9 h/d and plants were monitored for 14 d.

2.2.3 Topical application of the MAs

An outdoor experiment evaluated the influence of MAs put on the surface of topsoil on the growth of *P. vulgaris* (Fig. 2). For this, two 33- × 20- × 20-cm pots were used. Each pot had three perforated 2.5- × 20- × 2.5-cm troughs where the MAs and gravel were placed for the treatment and control pots, respectively. Gravel (835 grams) or MAs (430 grams) were evenly placed on the three troughs in the control or treatment pots respectively. This corresponded to an MA application of 65 tons/hectare. Six inches of the topsoil was placed at a bulk density of 1.53 ± 0.02 g/cm^3 (n = 2). Eight *P. vulgaris* seeds were sown in the top soil at 3.8-cm depth. Subject to natural weather conditions (e.g. precipitation, wind, evapotranspiration, sunlight), *P. vulgaris* survival, physiology, and growth dynamics were assessed for 52 d. Natural weather environments were monitored via a weather station located in the experiment area (Table 3).

2.3 Analysis

Soil pH (in 0.1% (w/v) $CaCl_2$ solution) was measured with an Orion pH meter and soil organic matter was quantified by the Loss-on-Ignition (SSSA, 1996) Total nitrogen and phosphorus concentrations in soils were analyzed by HACH methods following the Digesdahl digestion process. Soil texture classification was done with a hydrometer analysis (USDA, 2010)

Lead concentration in leaves and roots was determined by the LeadTrak method following the Digesdahl digestion process (HACH Method 8317). *P. vulgaris* shoot height and leaf number were measured. For the dry root: shoot ratio, roots and shoots were separated, dried at 105 °C overnight, stored in a desiccator to cool down to room temperature, and then weighed. Plant health was monitored by measuring leaf chlorophyll intensity with a chlorophyll meter (SPAD-502, Konica Minolta). Specific conductivity was analyzed with an Orion Specific Conductivity Meter Model 162.

3. Results and Discussion

3.1 Germination, survival, and growth of P. vulgaris *in the MAs-layered indoor pots*

There was 100% germination rate with statistically insignificant differences ($p > 0.05$) in cotyledon emergence between pots, indicating similar initial growth. However, survival rates varied from 50% (pots 1 and 4), 85% (pot 2), and 100% (pot 3), with higher survival rates in the MAs-layered pots. Pot 3 had a MAs layer closer to the roots than pot 2, possibly influencing the higher survival rate in pot 3.

Taller shoot heights were observed when *P. vulgaris* grew in the MAs-layered pots (pots 2 and 3) (Fig. 3). *P. vulgaris* had taller shoot height and more leaves in pot 2, which had 50% more topsoil than pot 3. Generally, a good correlation (R^2>0.84) was found between shoot height and leaf number. At the end of the experiment, Pb concentrations were zero or below the detection limit (5 μg/L) in dried leaf and root biomass.

The MAs did not physically interfere with root growth. However, gravel, which had similar physical characteristics to the MAs, retarded growth of *P. vulgaris* (Fig. 3). Therefore, the MAs likely provided micronutrients enhancing *P. vulgaris* growth. The concentrations of individual micronutrients were not quantified in this study. Instead, a subset of batch experiments was conducted for analysis of specific conductivity of varying MAs quantities in deionized water (0 to 50 g MAs/L). Specific conductivity was measured in water to obtain a rapid estimate of the dissolved solids concentrations (Sawyer et al., 2003). High reactor conductivity values were measured even at 5 g MAs/L (Fig. 4). The final conductivities after 72-h reaction time were 770 (5 g MAs/L) and 3,090 (50 g MAs/L) μS/cm. Therefore, the MAs used in the growth experiments likely provided various ionic micronutrients that enhanced *P. vulgaris* growth (Jala and Goyal, 2006).

3.2 P. vulgaris *shoot heights in the indoor pots with the MAs and topsoil mixture*

P. vulgaris grown in the control pot (100% topsoil) had the shortest, but statistically insignificant ($p > 0.05$), shoot heights for the 14 d experiment, compared to the two pots containing the mixture of MAs and soil. *P. vulgaris* grew slightly better with a greater amount of MAs (i.e. 1:2 w/w soil: MAs), although the differences were not statistically significant ($p = 0.784$). Therefore, MAs caused no physical interference and, instead, seem to serve as a chemical component that enhanced *P. vulgaris* growth.

Results found in the current study were in a good agreement with Punshon et al. (2002) who reported an increased biomass production of erosion-control grasses in the restoration of the eroded borrow with co-application of FA and poultry biosolids. Other studies also reported productivity enhancement of *Oryza*

Table 3
Key weather information during the outdoor experiment (Sep 17 ~ Nov 5, 2009)

(unit)	Temperature (°C)	Humidity (%)	Wind speed (km/h)	Rain intensity (mm/hr)	Solar radiation (W/m^2)	UV Index -	Evapo-transpiration (mm)
High	33.5	97	8	195.1	1133	16	0.69
Average	25.3	87	1.1	0.74	173	2.6	0.03
Low	19.9	49	0	0	0	0	0

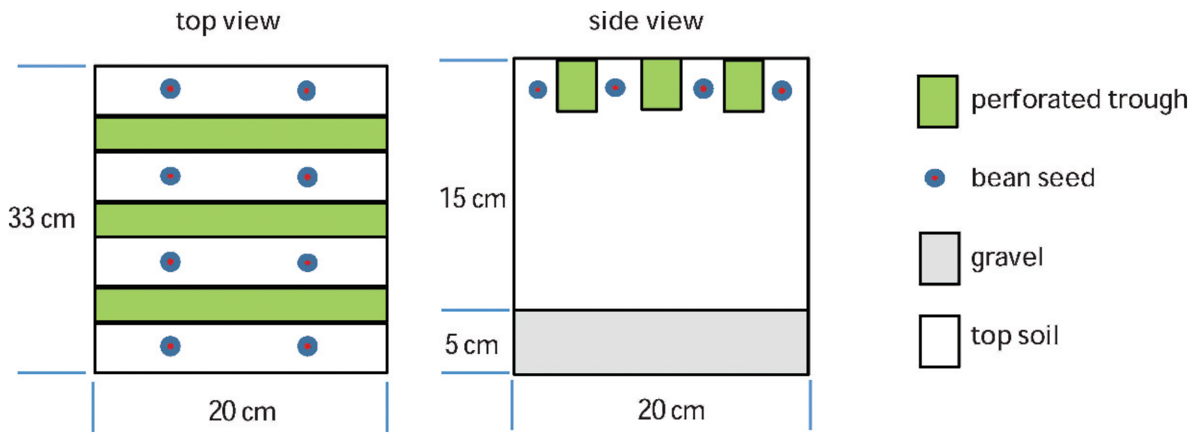

Fig. 2. Schematic diagram of the pots for the outdoor experiment with MAs on the surface of the top soil.

sativa (rice), *Spathiphyllum* Schott (peace lily), *Zea mays* L. (corn), *Glycine max* L. (soybean), and *Lycopersicon esculentum* (tomato) with FA amendment in soils (Mishra and Shukla, 1986; Kan and Kan, 1996; Chen and Li, 2006; Lee et al., 2006).

Utilization of CCPs in agriculture may not always be beneficial. Even a small quantity of FA amendment (5%) to soils caused significant reductions in growth, biomass, and yield responses of *Beta vulgaris* (palak) (Singh et al., 2008). Similarly, an FA application rate of 10% or greater reduced yield and chlorophyll concentration of *Zea mays* L. (corn) and *Glycine max* L. (soybean), although a smaller FA application rate of 2.5 to 5% increased the height, leaf area, chlorophyll and carotenoid content, and dry weight of both plants (Mishra and Shukla, 1986).

3.3 P. vulgaris *growth in the outdoor pots with MAs on the surface of the top soil*

P. vulgaris grown in the outdoor pots with MAs were taller and had more leaves than in the control pot (Fig. 5). As shown in Table 2, *P. vulgaris* were subjected to typical autumn weather in the subtropics. As designed, the rainwater leached through the troughs of the MAs or gravel and infiltrated to the topsoil in the pot. Similar to the indoor experiments, the enhanced *P. vulgaris* growth in the MAs-containing outdoor pot was likely attributed to the micronutrients leached from the MAs.

Chlorophyll intensity was monitored on every leaf suitable for measurement using the chlorophyll meter. *P. vulgaris* grown in the

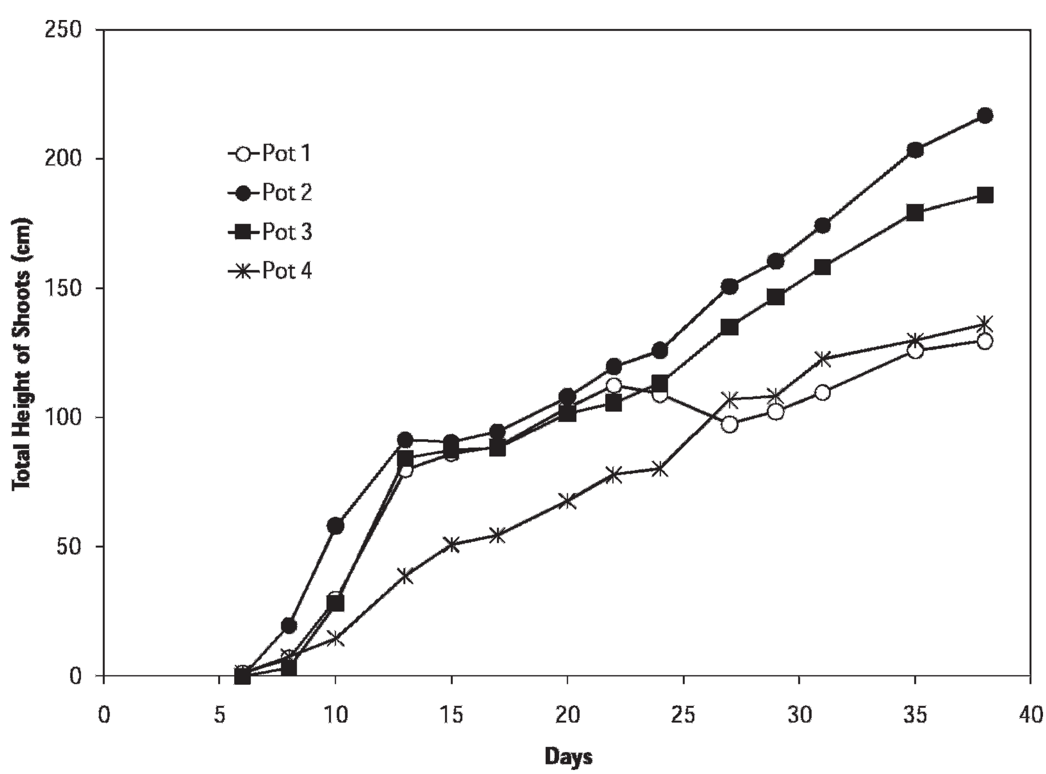

Fig. 3. Total shoot heights of *P. vulgaris* grown indoors in the presence (pots 2 and 3) or absence (pots 1 and 4) of MAs layer below the top soil. The numbers of *P. vulgaris* counted for the shoot heights were 3 (pot 1), 5 (pot 2), 6 (pot 3), and 3 (pot 4) according to the resulting survival rate, 50, 83, 100, and 50%, respectively.

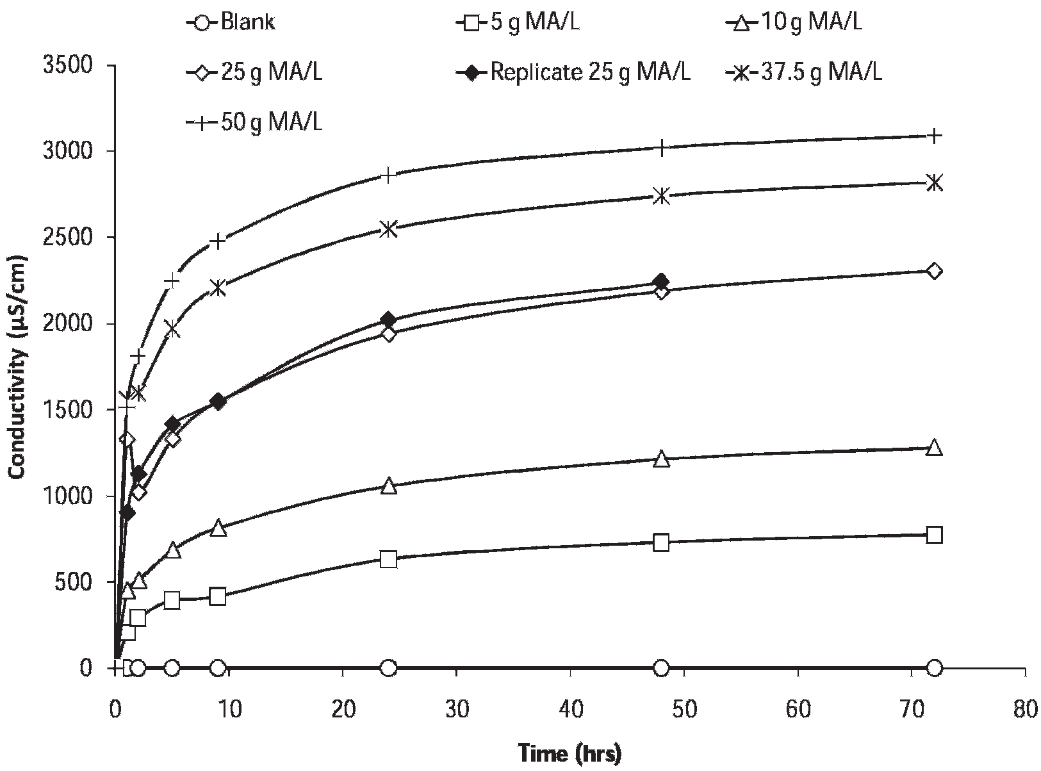

Fig. 4. Trend of conductivity development by the MAs in deionized water. The same MAs with a particle size of 2.36 to 9.53 mm that used for the plant experiments were tested.

MAs-containing pot had higher chlorophyll concentrations (Fig. 6). Chlorophyll is one of the major chloroplast components for photosynthesis, which allows plants to obtain energy from light. Therefore, relative chlorophyll content has a positive relationship with photosynthetic rate and, hence, plant health. For example, Manios et al. (2003) studied the effect of heavy metal accumulation on the leaf chlorophyll concentration in *Typha latifolia* (cattails). They found probable evidence of an inhibitory effect of heavy metal accumulation correlated with a decrease in chlorophyll concentration.

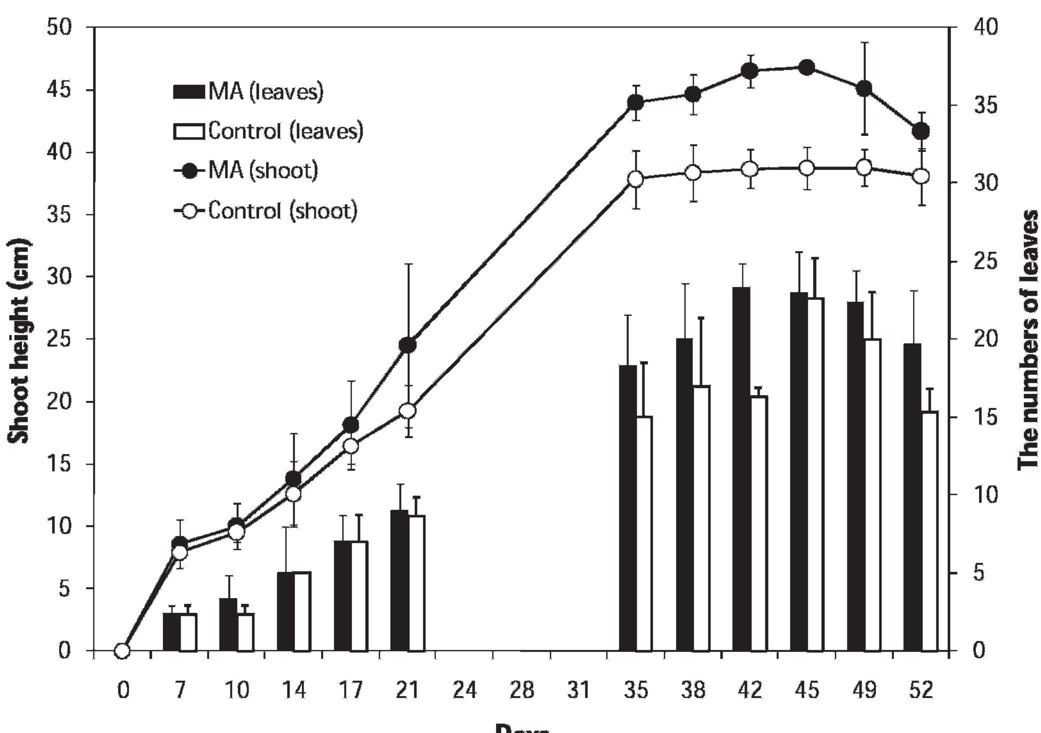

Fig. 5. *P. vulgaris* shoot heights and leaf number when grown outdoors with MAs on the surface of the top soil (average ± standard deviation, n=8).

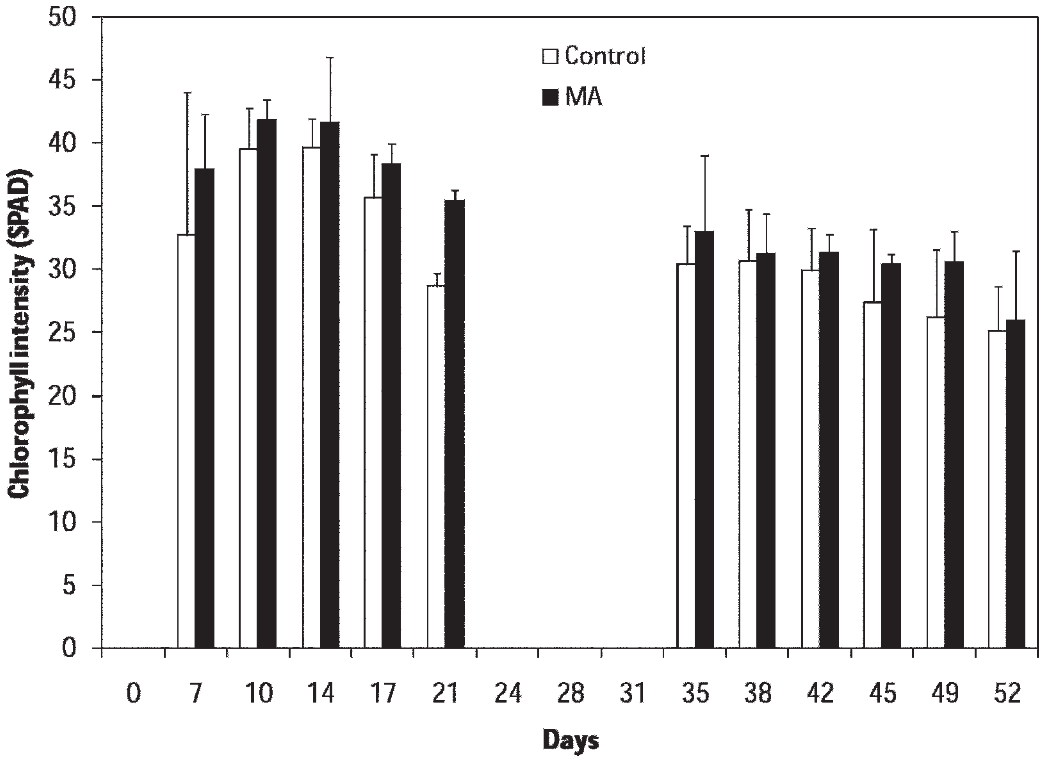

Fig. 6. Chlorophyll intensities (SPAD) of *P. vulgaris* grown outdoors with MAs on the surface of the top soil (average ± standard deviation, n=8). The same leaf of each plant was used for the measurement.

4. Conclusions

MAs, a solidified mixture of 2:1 (w/w) FA and BA were tested for their potential use as a subsoil substitute in restoration of open pits to phyto-viable land. Both indoor and outdoor growth experiments showed that *P. vulgaris* grew better under the influence of MAs at application rates of 65 to 800 tons/ha, having taller shoots, more leaves, and higher leaf chlorophyll intensity. MAs were shown to enhance the growth and quality of *P. vulgaris* when they were used as a subsoil substitute, although more detailed studies are needed to encompass other scientific and engineering aspects such as MA, plant and soil types, optimum MA application rates, and groundwater quality.

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