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Study on the Application of Fly Ash for Soil Amelioration

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Abstract

In this study, pot culture experiments were carried out to investigate the most suitable level of fly ash for the amelioration of soil that can enhance the management of fly ash. The fly ash recovered from the Mong Duong 2 coal-fired thermal power plant and had the main chemical composition of oxygen (43%), Si (26%), Al (15%), K (9%), and Fe (6%). The addition of fly ash to light texture soil increased some of the basic properties of the soil, such as moisture, cation exchange capacity, mechanical composition, and organic matter content. The results of the performance evaluation of an experimental crop (soybeans) showed the effects of the amended soil on the growth of the experimental plants, namely the number of fruits, number of nodules, and their dry biomass. The incorporation of manure into the sandy soil was amended with fly ash in the pot experiment as a single application of fly ash may not provide enough nutrients for plant growth despite its ameliorant effect on soil structure. The appropriate fly ash addition rate from 10-30% w/w is recommended in soil amelioration applications based on the results of this study. This research opens up an application direction for fly ash, a by-product generated from the operation of coal-fired power plants in Vietnam.

Keywords

Fly ash, coal-fired, power plants, soil amelioration

Introduction

The high demand for energy around the world as well as in Vietnam is mainly supplied by a huge number of coal-fired power plants. Fly ash is a by-product of a type of solid waste generated mostly from these thermal plants. In Vietnam, with consumption of nearly 100 million tons of coal per year for running thermal power plants in recent years, it is estimated that the average amount of created fly ash collected from ESP (Electrostatic Precipitation) Filter systems will increase from 30 million tons in 2025 to 38 million tons in 2030 (Prime Minister, 2016). Recently, the main response to this solid waste has only been disposing it in ash ponds surrounding the

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plants (Vietnam-Electricity-Corporation, 2018). Some environmental problems related to this unsafe storage method are soil, water, and air pollution as well as soil degradation.

Globally, fly ash can be widely reused as amendment materials such as in the construction industry (Nath & Sarker, 2011), ceramic industry (Kockal, 2012), catalytic production (Zhang *et al*., 2012), zeolite material synthesis (Ansari *et al*., 2014), and precious metal collection (Torralvo & Fernández-Pereira, 2011) as well as can have applications in environmental treatment materials (Pandey & Singh, 2010; Kanhar *et al*., 2020). Although, the reuse of this type of industrial waste for different purposes is always encouraged, these applications have been assessed as not being commensurate with the amount of fly ash generated from coal-fired power plants every year.

Based on the physical and chemical properties of fly ash, some studies investigating applications of this resultant combustion product as an ameliorant for light texture soil have been carried out (Grewal, 2001; Truter *et al*., 2006; Yadav & Pandita, 2019). Physically, different natural coal and combustion conditions will create different properties of produced fly ash. However, very fine particles with a low to medium bulk density as well as a high surface area (Thien *et al.*, 2019) have been considered as an amendment for altering the light texture, enhancing the water capacity, and improving the cation exchange capacity of soils. Agricultural utilization of fly ash has been proposed because of its considerable content of elements. Chemically, fly ash is rich in many macro and micro plant nutrients, including a high content of Si, Al, Fe, Ca, Mg, Na, and K (Korniejenko *et al*., 2019), and other trace elements such as B, Mo, S, Se, and Sr (Zierold & Odoh, 2020). Fortunately, heavy metal and radioactive element concentrations in most fly ash produced in Vietnam are below the permissible limits of QCVN 03-MT:2015/BTNMT for heavy metals such as As, Cd, Pb, Cu, and Cr (Sushil & Batra, 2006; Le Van Thien *et al*., 2016) and lower than the soluble threshold limit concentration for radioactive elements (Jambhulkar *et al*., 2018; Thien *et al*., 2019). In Vietnam, fly ash from the Pha Lai thermal power plant has been used as an ameliorant in coastal sandy soil. The results showed that fly ash significantly improved the moisture-holding and the acidity and cation exchange capacities (CEC) as well as the content of macronutrients of grey and sandy soils (Nguyen Thi Bich Ngoc, 2012; Le Van Thien *et al*., 2016; Thien *et al*., 2019). In this study, fly ash collected from the Mong Duong 2 power plant was added to sandy soil at different levels to investigate how this fly ash influences the physical and chemical properties of the soil as well as the productivity of experimental plants (soybean). The successful results could be considered a suitable solution to contribute to a more scientific based method for safely reusing the huge amount of fly ash produced in Vietnam.

Methodology

Research materials

Fly ash was collected from Mong Duong 2 thermal power plant in Cam Pha city, Quang Ninh province, Vietnam. The fly ash was captured by an electrostatic precipitation filter (ESP) system. The density of the fly ash was 2.24 g cm^{-3} and it had a moisture content of 2.1% (**Figure 1**).

The experimental sandy soil was collected from the top layer of a fruit orchard in Van Giang commune, Van Lam district, Hung Yen province.

Cultivated soils in the experimental pots were collected after 56 days of the experiment. The soil samples were then air-dried and passed through a 2.0-mm sieve for laboratory analysis. The main properties, namely pH, soil texture, cation exchange capacity, and moisture content, of these soil samples were analyzed to understand how this fly ash could influence the soil features.

Research methods

Fly ash analysis

The morphological and chemical compositions of the fly ash material were examined by scanning electron microscopy (SEM) coupled with energy-dispersive X-ray

Figure 1. Fly ash collected from an ESP system at the Mong Duong 2 thermal power plant

spectrometry (EDX) (FESEM S-4800, Hitachi). SEM analysis was conducted with 500x and 2000x magnifications. EDX analysis was at 1.060 keV. Heavy metals in the fly ash were analyzed by an Atomic Absorption Spectrometric (PinAAcle 900T, PerkinElmer).

Greenhouse pot experimental design method

To understand how fly ash influences the properties of soil and the growth of soybean plants, an experiment was carried out with five treatments (TM), namely TM1, TM2, TM3, TM4 and TM5, as shown in **Table 1**. The total weight of each experimental pot was set at 7,000g while the fly ash amount was a factor of 700g. The soil amelioration capacity was compared to the control pots without added fly ash.

Greenhouse pot experiments were conducted at Vietnam National University of Agriculture (VNUA) under normal conditions from May to June 2021. Ten day-old soybean plants (*Glycine max)* with an average height of 10 cm were selected to plant in the pots. Three soybean plants of the same height were planted in each experimental pot. Fertilizer (NPK 17-12-5) was supplemented four times during the experiment at a dosage of 1.1g per pot. All experiments were performed in triplicate.

Soil properties analysis

Soil properties, namely soil texture, cation exchange capacity (CEC), and moisture content, were analyzed. Soil texture was examined following TCVN 5257 - 90 Cultivated soil - Determination of Particle Size Distribution; soil CEC was determined according to TCVN 8568:2010 - Soil quality - Method for determining the cation exchange capacity (CEC) by the ammonium acetate method; and soil moisture was analyzed following TCVN 4048:2011 Soil quality - Determination of the humidity and absolute dryness coefficient.

Plant growth analysis

The basic growth properties of the experimental plants (soybean), including plant height, number of leaves, and plant bio-mass, were measured. The plant height, number of leaves, and width of the leaves were measured on the same day (Monday) every week. Other features of the yield properties such as the number of fruits, number of nodules, and the dry biomass of the soybean plants were examined after 56 days of cultivation (**Figure 2**).

Data analysis

Paired t-test was used to clarify the significant differences between means at *P* <0.05. All of the analytical data were processed and indicated by SigmaPlot 14 software.

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Table 1. Experimental design

Experimental compositions	Control	TM1	TM2	TM3	TM4	TM5
Fly ash (g)	0	700	1,400	2,100	2,800	3,500
Manure (g)	20	20	20	20	20	20
Soil amount (g)	6,980	6,280	5,580	4,880	4,180	3,480
Total (g)	7,000	7,000	7,000	7,000	7,000	7,000
Ratio (%)	0	10	20	30	40	50

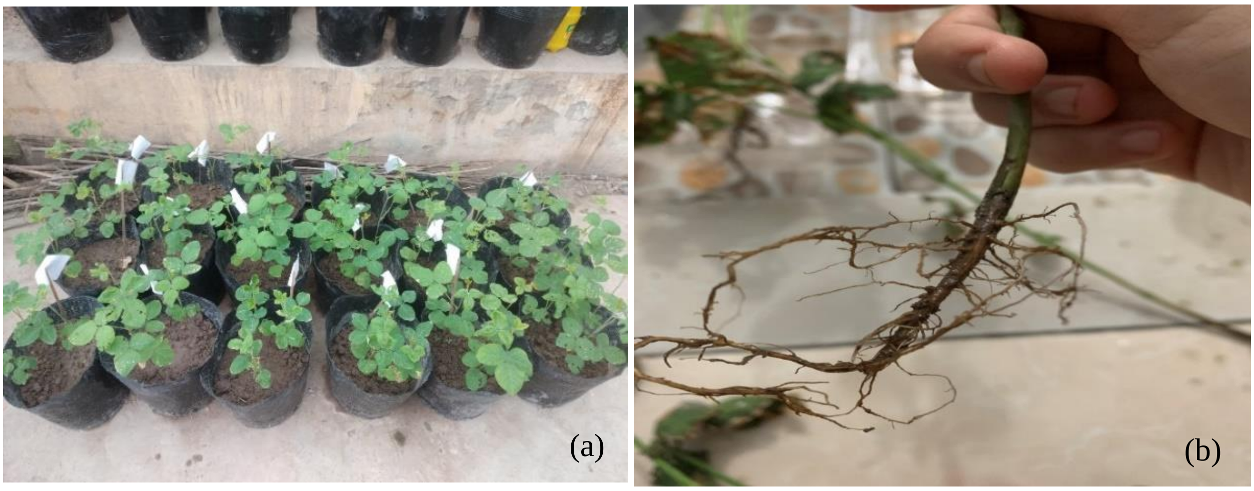

Figure 2. Soybean plants (a) and nodules (b) in the pot experiment

4048:2011 Soil quality - Determination of the humidity and absolute dryness coefficient.

Plant growth analysis

The basic growth properties of the experimental plants (soybean), including plant height, number of leaves, and plant bio-mass, were measured. The plant height, number of leaves, and width of the leaves were measured on the same day (Monday) every week. Other features of the yield properties such as the number of fruits, number of nodules, and the dry biomass of the soybean plants were examined after 56 days of cultivation.

Data analysis

Paired t-test was used to clarify the significant differences between means at P <0.05. All of the analytical data were processed and indicated by SigmaPlot 14 software.

Results and Discussion

Physicochemical properties of fly ash

Particle size distribution of fly ash

The resultant combustion product from coal-fired thermal plants includes bottom ash and fly ash. While bottom ash can easily be collected from the furnace because of its heavy and large dimension, fly ash, with a very fine particle and low weight, can only be captured from an electrostatic precipitation filter (ESP) system.

The ESP fly ash from the Mong Duong 2 thermal power generator had a round and very fine particle size ranging from 0.2-8.0µm. **Figure 3** shows that these fine particles were aggregated into micron and sub-micron sizes. This result is compatible with previous reports about fly ash (Khairul Nizar *et al*., 2014; Thien *et al*., 2019). Based on these special properties, it is believed that adding fly ash as an amendment to low texture soils might change the soil's properties,

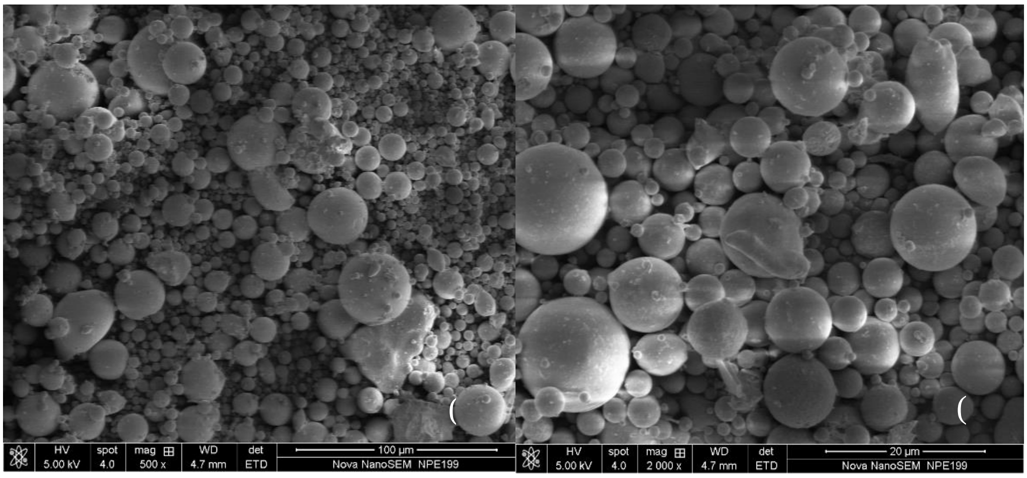

Figure 3. Scanning electron micrographs of the fly ash at (a) 500x and (b) 2000x magnification

such as the water holding capacity, cation exchange capacity, water movement, and bulk density (Pathan *et al*., 2003). With the presence of fly ash, the proportion of sand, silt, and clay-sized particles in the soil will be adjusted.

Chemical composition of the fly ash

By using EDX, the fly ash was found to be mainly composed of oxygen (43%), Si (26%), Al (15%), K (9%), Fe (6%), and other elements, such as very low concentrations heavy metals or radioactive elements beyond the resolution of this technique (1%). It can be seen that the fly ash of the Mong Duong 2 thermal power plant contained relatively large concentrations of macro-elements (K) and intermediate elements (**Figure 4**). These results indicate that additions of fly ash could be very beneficial to improve the productivity of soils with low CEC and poor mineral and nutrient contents. In addition, the fly ash also contained trace elements, which are essential nutrients for soil and plants.

The chemical properties, especially the heavy metal content, of fly ash are also factors that can influence the physical properties of the soil. As shown in **Table 2**, the contents of some heavy metals in the fly ash were many times lower than the threshold of QCVN 03-MT:2015/BTNMT – National technical regulations on the allowable limits of heavy metals in the soil. This means the fly ash is relatively safe for using as a source to supplement the soil. In a study regarding the investigation of heavy metals in fly ash of five thermal power stations of Pha Lai, Mong Duong I, Mong Duong II, Ha Khanh, and Ninh Binh, it was shown that the amounts of some heavy metals, such as Cu, Cr, and Ni, were the same as compared to this study, but other elements, such as Zn, Cr, Pb and Cd, were higher (Thien *et al*., 2019). These differences may be due to the different types of materials combusted in these power stations.

Effects of fly ash amendment on soil properties

The research measured some major features of the soil, namely the pH, moisture, OM, CEC, and texture, in the pot experiment after 56 days (**Table 3**). It was discovered that the most frequent tendency in terms of changes of the soil properties after the experimental period was the increasing trend in moisture, CEC, and texture (TM1, TM2, and TM3). These parameters, on the contrary, tended to have a decreasing trend when larger amounts of fly ash were added to the soil (TM4 and TM5). The pH value of the soils remained unchanged during the experiment.

Soil texture

Due to the very fine particles, the addition of fly ash into the experimental soils as an amendment showed that the soil texture in this experiment changed as the proportion of clay and lime markedly increased. When the fly ash was added to the soil with a ratio varying from 10%

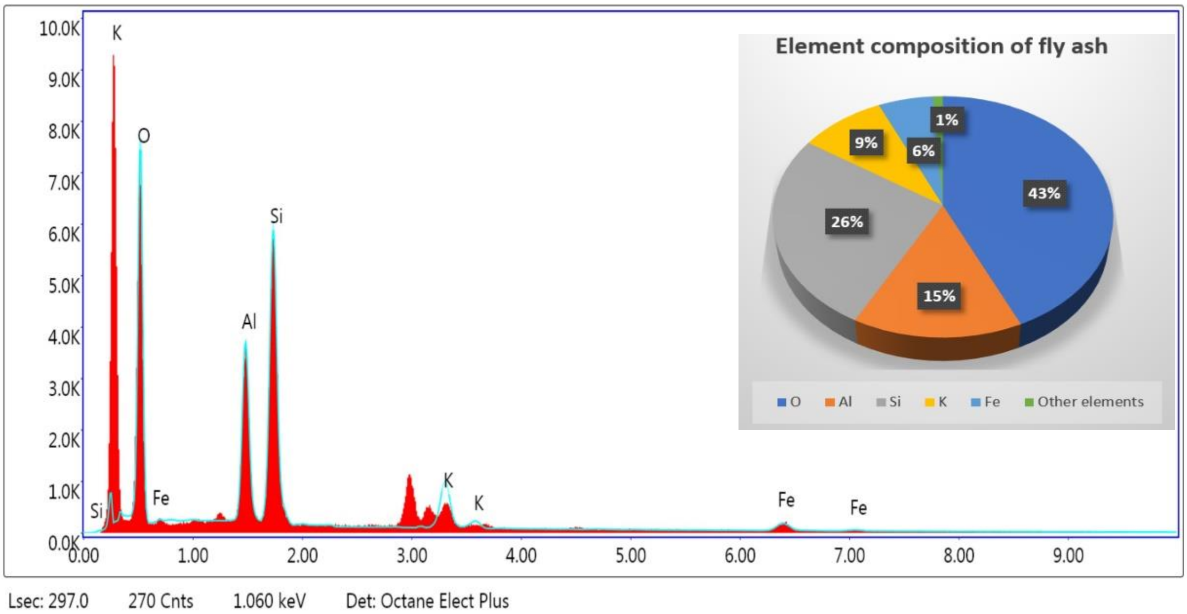

Figure 4. Chemical composition of fly ash by EDX technique

Table 2. Heavy metal contents in the fly ash

No.	Elements	Concentration (mg kg^{-1})			Average (mg kg^{-1})	SD	QCVN 03 (mg kg^{-1})
		T1	T2	T3			
1	Zn	30.4	33.1	34.2	32.57	1.96	200
2	Cr	77.2	76.1	70.8	74.70	3.42	150
3	Mn	251.4	248.5	236.7	245.53	7.79	-
4	Cu	39.6	40.9	42.7	41.07	1.56	100
5	Ni	37.4	33.9	35.7	35.67	1.75	-
6	Pb	22.8	20.9	24.1	22.60	1.61	70
7	As	14.6	12.2	11.9	12.90	1.48	15
8	Cd	0.22	0.21	0.22	0.22	0.01	1.5
9	Hg	0.994	0.944	0.975	0.97	0.03	-

Table 3. Effects of the addition of fly ash on the physicochemical properties of the soil

Soil properties	Control	TM1	TM2	TM3	TM4	TM5
pH	7.13 ± 0.01	7.14 ± 0.01*	7.15 ± 0.01**	7.15 ± 0.01*	7.15 ± 0.01**	7.16 ± 0.01**
Moisture (%)	1.33 ± 0.14	1.73 ± 0.48	3.95 ± 1.09*	5.29 ± 1.14*	4.56 ± 0.34**	2.41 ± 0.14**
OM (%)	2.32 ± 0.14	2.44 ± 0.16	2.71 ± 0.16*	2.74 ± 0.08*	2.55 ± 0.18	2.51 ± 0.17
CEC (meq/100 g)	10.96 ± 0.05	11.21 ± 0.43	11.93 ± 0.23**	12.64 ± 0.10	12.93 ± 0.05*	12.74 ± 0.57**
Clay (%)	11.96 ± 0.15	12.03 ± 0.25**	13.06 ± 0.38**	14.53 ± 0.2**	15.33 ± 0.15**	17.20 ± 0.15**
Lime (%)	26.33 ± 1.31	32.53 ± 3.36*	34.13 ± 0.80**	35.26 ± 0.36**	35.93 ± 0.82**	38.20 ± 2.45*
Sand (%)	61.70 ± 1.17	55.43 ± 3.16*	52.80 ± 1.17**	50.20 ± 0.26*	48.73 ± 0.68**	44.60 ± 2.30*

Note: (*) and (**): The differences compared to the control samples, P ≤0.05 and P ≤0.01. (two sample t-test) to 50% (TM1 to TM5), the lime content increased significantly from 26.33 ± 1.31% to 38.20 ± 2.45%. Meanwhile, the clay proportion increased less drastically from 11.96 ± 0.15% to 17.20 ± 0.15%. On the contrary, the sand amount decreased gradually from 61.70 ± 1.17% to 44.60 ± 2.3% (**Figure 5**).

With the main components being fine-sized solid particles, the addition of fly ash to the soil significantly changed the mechanical composition of the soil. The soil before the experiment was loamy sand (clay 11.96 ± 0.15, lime 26.33 ± 1.31, and sand 61.70 ± 1.17). However, after adding fly ash, the experimental soil was classified as a light soil. The addition of fly ash at 70 t ha^{-1} has been reported to alter the texture of sandy and clay soils to loamy. Changes in the physical composition will influence other soil physical properties such as moisture content (three times higher) and soil bulk density (Pathan *et al*., 2003).

Soil moisture content

Figure 6 shows that the addition of fly ash to the soil had a large effect on the soil moisture content. While the soil moisture in the control sample (no addition of fly ash) after the experiment was only 1.33 ± 0.14%, the moisture of the soil in the treatment samples significantly increased from 1.73 ± 0.48% to 5.29 ± 1.14% (TM1 to TM3) and then decreased from 4.56 ± 0.34% to 2.41 ± 0.14% (TM4 and TM5). This showed that fly ash can be used to improve the moisture value of soil. However, the results in this study showed that adding an excessive amount of this material decreases its effectiveness . This tendency might be explained by the particle size distribution of the fly ash. Soil moisture content plays a very important role in dictating crop productivity because this property of soil has a significant effect on both chemical and biological processes in the soil mass. Improvement of the moisture content in soil is considered an effective method to enhance its production capacity (Dass *et al*., 2011). Because it consisted mainly of very fine particles, an excessive amount of fly ash added into the soil, as in TM5 (50% of fly ash and 50% of soil), might increase the resistance of hydraulic conductivity in the soil (Phani & Sharma, 2004).

Soil cation exchange capacity (CEC)

Based on the CEC of the original soil (10.96 ± 0.05 meq.100 g^{-1}), this value steadily increased from TM1 (11.21 ± 0.43 meq 100 g^{-1}) to TM5 (12.74 ± 0.57 meq 100 g^{-1}) in which the fly ash amended from 10% to 50% w/w (**Figure 7**). The fly ash was mainly composed of fine particles around 0.2-8.0μm in diameter.

Cation exchange capacity (CEC) is one of the most important properties of soil. This characteristic is widely utilized to assess a soil's improvement efficiency. Fly ash-treated soils might change in mineralogy composition, and thus, the absorption capacity of the soil might simultaneously change.

Effects of fly ash amendment on plant growth

In 8-week period (equivalent to 56 days) of the experiment, the height of the plants, the number of the leaves, and the width of the leaves were measured every Monday. The effects of fly ash on the growth and yield of the experimental soybean plants are shown in **Table 4**.

Effects on the plant height and width of leaves

The average rate of growth in soybean height and leaf width during the experiment ranged from 0.2 ± 0.18 to 0.35 ± 0.21 cm day^{-1} and from 0.13 ± 0.11 to 0.16 ± 0.32 cm day^{-1}, respectively (**Table 4**). In general, the initial research results showed that some growth indices of soybean increased slightly after fly ash supplementation (TM1, TM2, and TM3) compared to the control samples. However, these growth indexes tended to decrease correspondingly when the fly ash content increased (TM4 and TM5).

Fly ash contains elements like Ca, Fe, Mg, and K, which are essential to plant growth. Applications of fly ash at 10 and 20 t ha^{-1} improved rice yield from 1.02 to 3.83 t ha^{-1} in the first year and 4.65 t ha^{-1} in the second year (Tiwari *et al*., 1992).

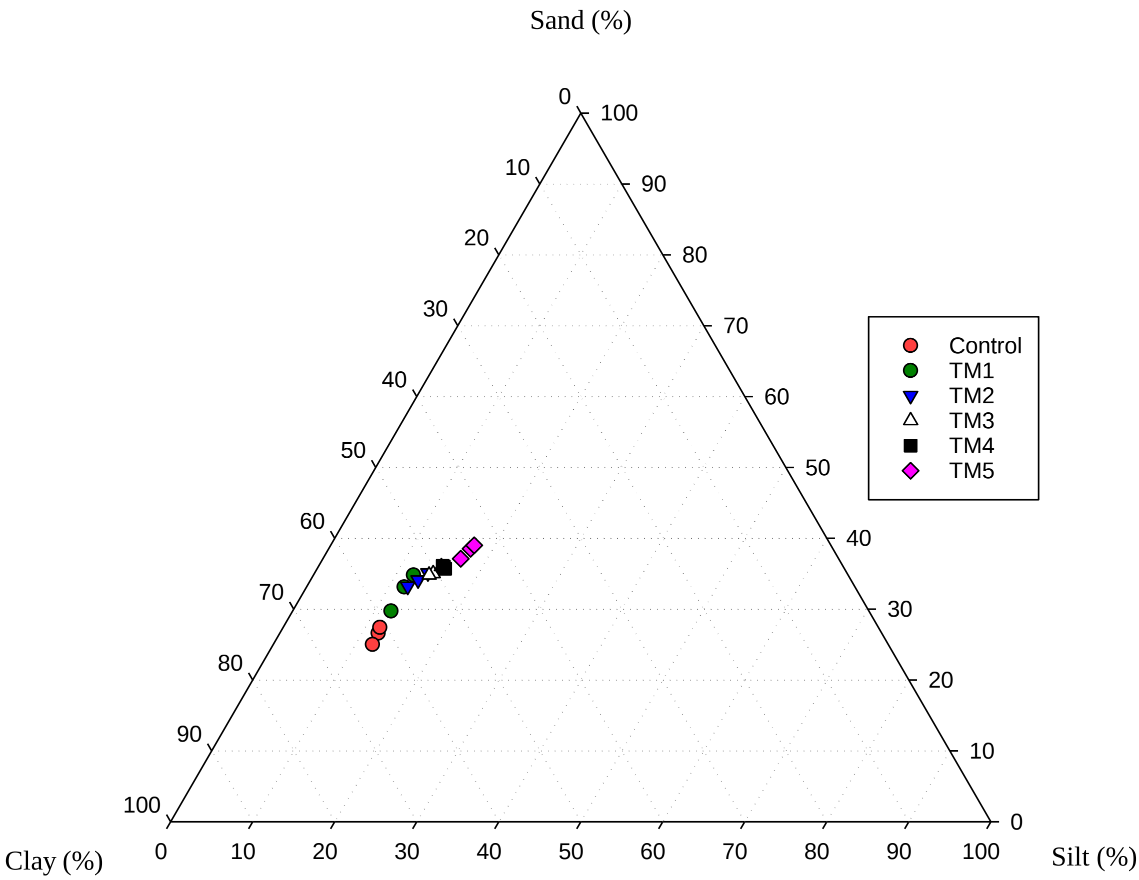

Figure 5. Changes in soil texture after adding fly ash

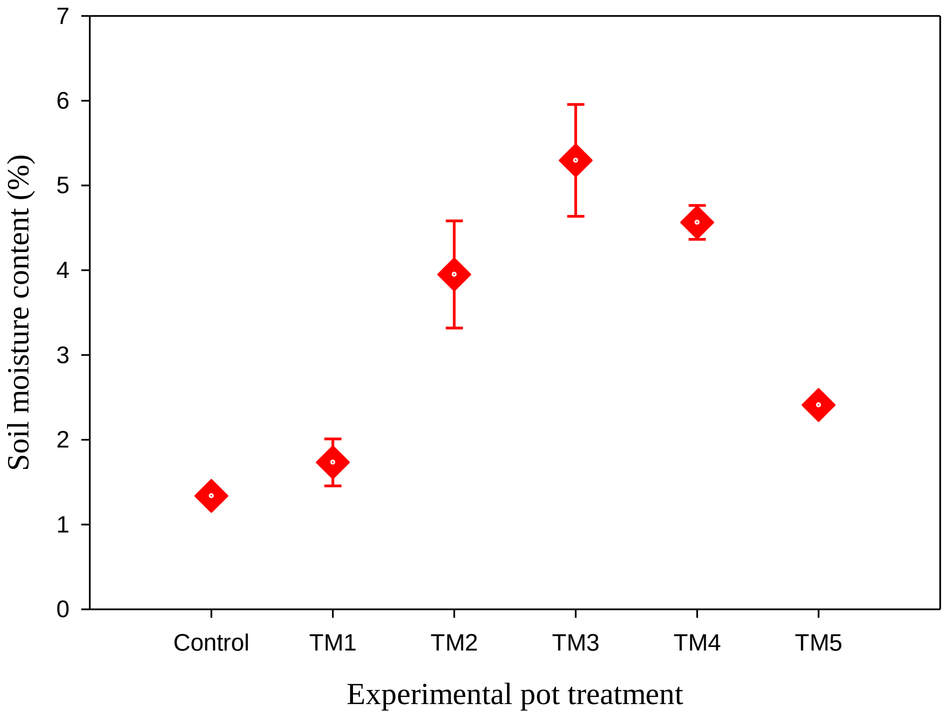

Figure 6. Effects of the addition of fly ash on soil moisture content

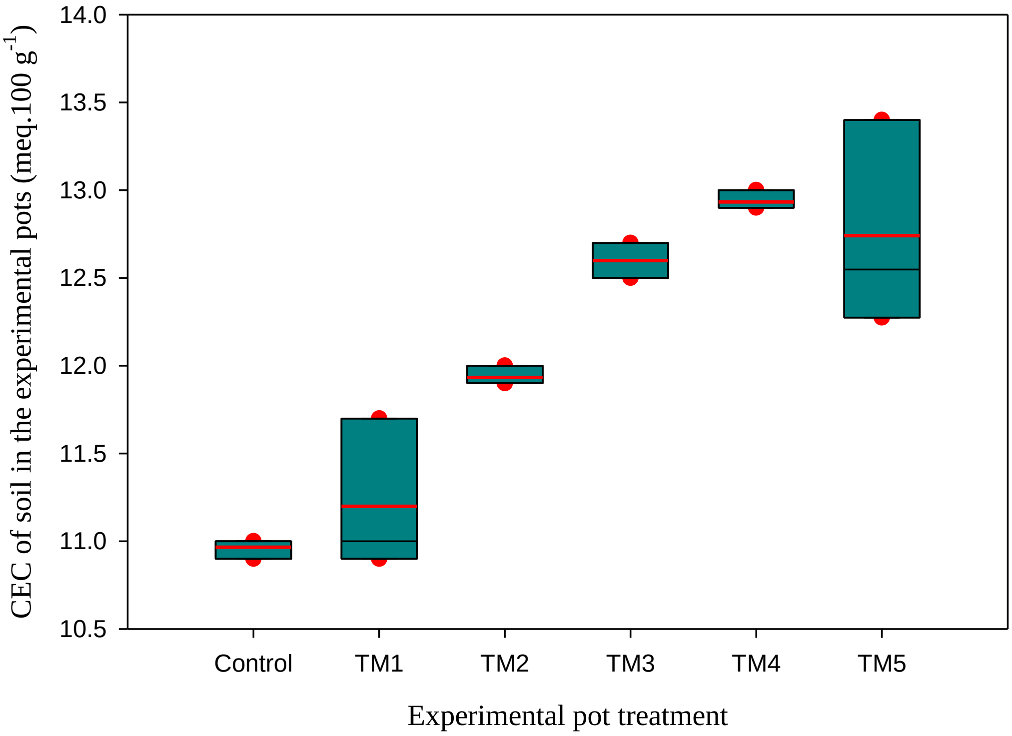

Figure 7. Effects of fly ash on the CEC of soil

Table 4. Effects of fly ash on the growth and yield of soybean plants

Growth parameters	Control	TM1	TM2	TM3	TM4	TM5
Height of plant (cm day^{-1})	0.20 ± 0.18	0.23 ± 0.20	0.35 ± 0.21	0.23 ± 0.16*	0.20 ± 0.13**	0.22 ± 0.14*
Width of leaves (cm day^{-1})	0.13 ± 0.11	0.13 ± 0.10*	0.16 ± 0.32	0.14 ± 0.11	0.12 ± 0.08	0.12 ± 0.06**
Number of fruits	11.22 ± 1.93	12.44 ± 0.19**	15.34 ± 1.15*	12.22 ± 0.39**	10.94 ± 0.58**	10.11 ± 0.51**
Number of nodules	21.0 ± 2.02	22.67 ± 2.52	29.0 ± 1.73***	29.67 ± 3.51**	27.0 ± 2.65**	27.0 ± 1.0***
Dry biomass (g pot^{-1})	4.3 ± 1.75	4.95 ± 1.86	5.24 ± 1.81	3.96 ± 1.90	3.04 ± 1.24	2.68 ± 0.51

Note: (*), (**), and (***):The differences compared to the control samples, P ≤0.1; P ≤0.05 and P ≤0.01 (paired t-test).

Effects on yield productivities

Some properties of the soybean plants in the experimental pots, namely the number of fruits, number of nodules, and dry biomass, were collected after 56 days.

The number of fruits. The number of fruits harvested after the period of the experiment was significantly different between pots. In comparison with the control sample, the fruits harvested from the pots increased from 12.44 ± 0.19 (TM1) to 15.34 ± 1.15 (TM2) but then reduced to 12.22 ± 0.39 (TM3) and to around 10.94 to 10.11 in the TM4 and TM5 treatments, respectively. This adverse effect was partly attributed to salinity caused by higher levels of sulfate, chloride, carbonate, and bicarbonate in the fly ash-amended soils (Singh & Siddiqui, 2003).

The number of nodules. Similar to the number of fruits, when fly ash was added to the soil, the number of nodules obtained from the experimental soybean plants also tended to increase gradually. This figure increased from 22.67 ± 2.52 to 29.67 ± 3.51 and then decreased again in the treatments with higher amounts of supplemental fly ash. The number of nodules is a parameter that reflects the properties of the soil. A large number of nodules means the soil has the ability to provide available P (Gaind & Gaur, 2002) and the nodules work to further enhance the productivity of the amended soil.

Dry biomass. Unlike the number of fruits and nodules, the soybean dry biomass obtained after the experiment period had less variation among the treatments as well between each treatment and the control.

The response effects in changing from useful to dangerous depend on the amount of added fly ash (Grewal, 2001). It can be seen that the growth indices of the experimental beans (number of fruits, number of nodules, and dry biomass) had a close relationship with some physicochemical properties of the soil. The formulations with high soil improvement efficiencies (TM2, TM3, and TM4) improved the growth properties of the experimental plants compared with the control samples without added fly ash. Similar to the physicochemical properties of the soil, supplementing too much fly ash (TM4 and TM5) reduced the effectiveness of improving the nutritional and growth parameters of the soybean plants. According to the type of added fly ash, such amendments could also provide minerals and aid nutrient retention by increasing the cation exchange capacity (CEC). This might be the reason that increases of the CEC and other factors such as the water capacity holding and soil texture influence the growth efficiency of plants (Pathan *et al.*, 2003).

Conclusions

The fly ash collected from the Mong Duong 2 coal-fired thermal power plant had the main chemical composition of oxygen (43%), Si (26%), Al (15%), K (9%), Fe (6%), and others (1%); and a fine particle size distribution (0.2 - 8.0 µm) was predominant (87.3%).

Initial research results indicated that the addition of fly ash to the soil contributed to improving some physicochemical properties of the soil. The additional fly ash increased the basic soil parameters of moisture, CEC, and mechanical composition, as well as the OM content. However, the addition of high fly ash contents (40-50% w/w) increased the bulk density of the soil as well as reduced its moisture content.

Through the improvement of the soil composition and properties, the performance evaluation of an experimental crop (soybeans)

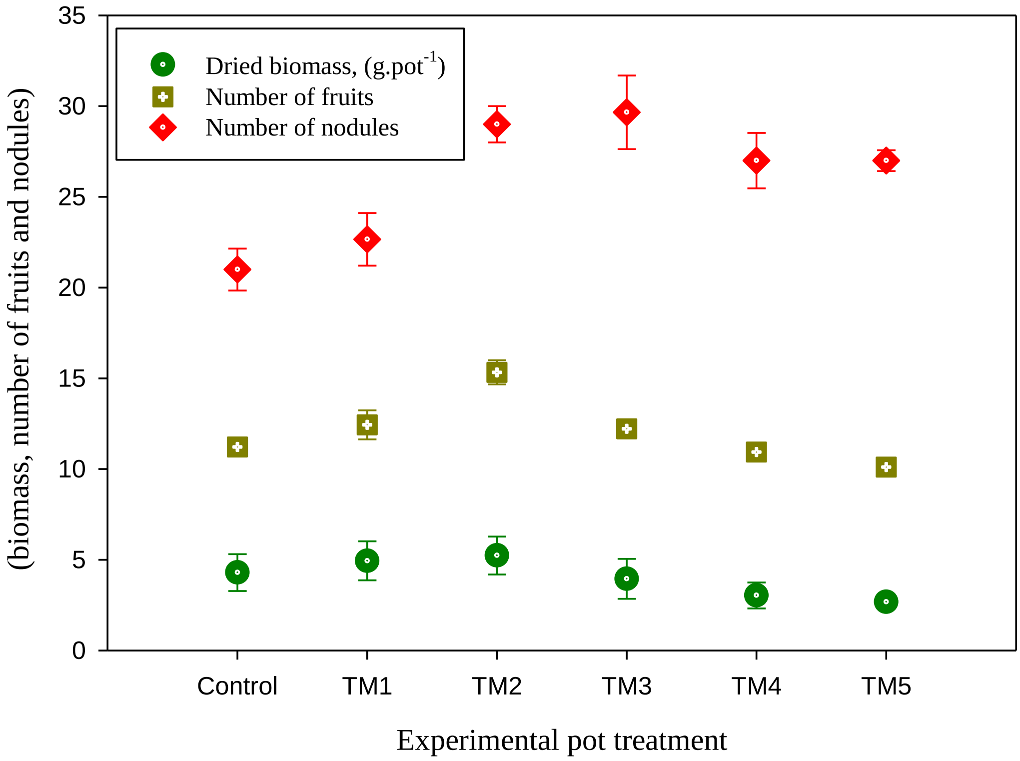

Figure 8. Effects of fly ash on the properties of soybean plants

showed the initial effects of the soil on plant growth and development through analysis of the number of fruits, number of nodules, and dry biomass.

Although the results showed a positive effect of fly ash addition on crop performance, an excessive addition of fly ash content had a negative impact on soil quality, thereby reducing soil quality as well as the growth and development of the experimental plants. The addition rate from 10 to 30% w/w is recommended in soil amelioration applications based on the results of this study.

Acknowledgements

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