Influence of Fly Ash as a Soil Conditioner on the Growth and Yield Performance of Napier Grass (*Pennisetum purpureum*)

Songyos Chotchutima,[a,]* Arunee Wongkaew,[a] Jetsada Authapun,[a] Ramida Krumsri,[a] Wan Mohd Nazri Wan Abdul Rahman,[b] and Lee Seng Hua [b]

Fly ash can enhance soil structure, nutrient availability, and water retention, making it a promising soil conditioner for agricultural applications. The growth and yield performance of Napier grass (*Pennisetum purpureum*) cultivar Pak Chong 1 was evaluated under different soil treatments. The control treatment consisted of 313 kg/ha NPK (Nitrogen, Phosphorus, and Potassium), 1,563 kg/ha dolomite, and 6,250 kg/ha manure, while fly ash was applied at levels of 1,563, 3,125, 6,250, and 12,500 kg/ha. Growth parameters such as plant height, number of tillers per clump, leaf-to-stem ratio, dry-to-fresh weight ratio, and heavy metal accumulation were examined. The fly ash significantly increased plant height, tiller number, and biomass yield compared to the control in most cutting cycles. However, the control occasionally exhibited higher leaf-to-stem ratios, suggesting that fly ash promotes stem growth more than leaf expansion, indicating an advantage for biomass production. Notably, the 3,125 kg/ha fly ash treatment resulted in considerable lead accumulation in leaves; however, this Pb originated from the native soil, not the fly ash, which had non-detectable levels. Higher fly ash levels (*e.g.*, 12,500 kg/ha) effectively reduced Pb uptake, indicating the need for dosage optimization to ensure heavy metal immobilization.

DOI: 10.15376/biores.21.1.2080-2100

Keywords: Fly ash; Growth; Napier grass; Soil conditioner; Yield

Contact information: a: Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand; b: Department of Wood Industry, Faculty of Applied Sciences, Universiti Teknologi MARA Pahang Branch Jengka Campus, 26400 Bandar Tun Abdul Razak, Pahang, Malaysia;
** Corresponding author: fagrsyc@ku.ac.th*

INTRODUCTION

Fly ash is a significant by-product of coal power generation, with substantial annual production that continues to increase due to rising power demand. The use of coal fly ash presents economic and environmental challenges. At present, the majority of this material is relegated to landfills, notwithstanding its significant liming properties and prospective agricultural applications (Yunusa *et al.* 2012; Ukwattage *et al.* 2013; Yao *et al.* 2015). Fly ash is a potentially hazardous and environmentally detrimental byproduct generated by coal-fired thermal power plants, and its disposal represents a significant global challenge. The environment suffers significantly from its adverse effects. Thus, sustainable strategies are essential for enhancing the efficient use of resources across various sectors (Ahmed *et al.* 2021). Rather than classifying it as waste, techniques are being devised for its environmentally sustainable application in agriculture.

The physicochemical characteristics of fly ash render it beneficial for plant development. It supplies a significant quantity of vital macronutrients, including calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), boron (B), sodium (Na), phosphorus (P), and potassium (K). Nonetheless, the nitrogen (N) present is not available for plant absorption, as it exists in the form of heterocyclic compounds (Jambhulkar *et al.* 2018). Furthermore, the addition of fly ash improves the water retention of coarse, textured soils, such as sandy soils, due to the presence of highly porous silt- and clay-sized particles. Moreover, the incorporation of fly ash facilitates the clustering of fine soil particles in the underlying zone (Yunusa *et al.* 2012; Ukwattage *et al.* 2013; Yao *et al.* 2015).

Numerous prior studies have evaluated the effectiveness of fly ash in promoting plant growth and yield in various species, including tomato, potato, cabbage, pea, wheat, mustard, oats, and sunflower (Mittra *et al.* 2005; Katiyar *et al.* 2012). Moreover, it has been documented that the utilization of fly ash positively affects the augmentation of phytochemical compounds in plants, notably resulting in a substantial increase in carotenoid levels in the leaves of black gram (Rajiv and Prakash 2012).

Napier grass (*Pennisetum purpureum* Schumach) is a highly promising forage species for energy and pasture use. It is characterized by rapid growth, substantial tiller production, and drought resistance. It is high in protein, making it appropriate for ruminants, and exhibits positive reactions to water and fertilizer, enabling continuous cultivation and efficient silage production for livestock during arid periods (Tudsri *et al.* 2002). Napier grass can reach harvest readiness in about 60 days, and its significant yield, averaging between 90 and 120 tons per hectare. These characteristics establish it as a substantial energy source with a high calorific value of approximately 16 MJ/kg (Haegele and Arjharn 2017; Pincam *et al.* 2017). Thus, Napier grass is extensively utilized as a solid fuel in numerous industrial applications and has the potential for conversion into biogas for electricity production (Singbua *et al.* 2017). The varied applications of Napier grass require an increase in its production to satisfy the demand for energy.

This study aimed to evaluate the efficacy of fly ash in enhancing Napier grass yield and alleviating pollution from fly ash waste accumulation. Specifically, this study investigated the effects of varying concentrations of fly ash on the growth and yield performance of Napier grass, considering its application as a soil conditioner to maximize its potential as a high-biomass energy crop.

METHODOLOGY

Experimental Site and Design

The experiment was conducted at the Buriram Livestock Research and Testing Station in Buriram Province, Thailand (15°7'43.32"N, 103°14'29.04"E) under rain–fed conditions for two years from June 2017 to June 2019. The soil properties of the field experiment were characterized by loamy sand texture, moderately acidic (pH of 5.9), low level of organic matter content (OM = 0.6%), moderate levels of available phosphorus (P: 18.7 mg/kg) and potassium (K: 54.0 mg/kg), with calcium and magnesium at suitable levels (Ca: 70.7 mg/kg and Mg: 284 mg/kg). The experimental design was a randomized complete block design (RCBD) with three replications. The treatments consisted of eight different soil conditioner management strategies, including: control (Ctrl) – no fly ash or chemical fertilizer; nitrogen, phosphorus, and potassium (NPK) fertilizer (15–15–15; (F)) at a level of 313 kg/ha, which is the standard dosage for farms (F); dolomite at 1,563 kg/ha (DF) combined with F (DF); manure at 6,250 kg/ha (MF) combined with F (MF); Fly ash at 1,563 kg/ha combined with F (FF1563); FF3125; FF6250; and FF12500. The selection of dolomite and manure application levels (1,563 kg/ha and 6,250 kg/ha, respectively) was based on local agricultural recommendations for field crops in the region. The fly ash levels were determined based on preliminary studies and were intended to cover a broad range of application for effective soil liming and nutrient release. The fly ash properties are summarized in Table 1.

Table 1. Physico-chemical Properties of Fly Ash

Parameters	Fly ash (FA)
pH (Alkaline-acidic)	12.7 (strongly alkaline)
Organic Matters (OM) (%)	9.80
Phosphorous (%)	0.26
Potassium (%)	1.71
Calcium (%)	1.16
Magnesium (%)	4.60
Sodium (%)	0.32
Iron (%)	2.53
Aluminum (%)	1.25
Sulfur (%)	1.29
Lead (%)	Non-detected
Cadmium (%)	Non-detected
Arsenic (%)	0.0012
SiO_2 (%)	29.67
Al_2O_3 (%)	18.60
MgO (%)	17.01
Fe_2O_3 (%)	16.76
K_2O (%)	8.04
CaO (%)	3.69

Establishment and Management

Napier grass cultivar Pak Chong 1 is a hybrid species, crossed between *P. purpureum* and *P. glaucum*. The stem of Napier grass was chopped into pieces with three nodes per piece and propagated in polythene bags (size 10 × 23 cm^2) for 4 to 5 weeks before being transplanted into the experimental area, with a spacing of 1 × 1 m^2 for both inter-row and intra-row spacing. The size of each plot was 5 × 6 m^2. Every two weeks, each plot received treatment based on its specific protocol, and urea (46–0–0) was applied with rate 188 kg/ha after each cutting interval. Weed control, using hand tools, was conducted manually twice: once at one month and again at two months after planting, with no irrigation provided.

Data Collections

Plant height was measured each month after planting from ground level to the end of the shoot using a stick meter on 10 randomly selected plants per treatment. The number of tillers per clump was also recorded monthly from the same 10 randomly selected plants for each treatment. Harvesting was performed every three months after planting, with fresh and dry weight yield measured in kg/ha. Fresh weight yields were taken from a central row, where plants were cut to 15 cm above ground level. A 500-g fresh sub-sample was then separated into stems and leaves (including leaf blades and sheaths) for the leaf–to–stem ratio, sun-dried for one day, and dried in a hot air oven at 75 °C for 72 h. The dry weight yield was recorded to calculate the percentage of dry weight and the leaf–to–stem ratio.

Elemental Analysis

A total of 500 g of dried samples of plant were powdered for elemental analysis using the wet digestion method. Briefly, 0.25 g of each powder sample was placed in a 50-mL flask, and 6.5 mL of a mixed acid solution was added, consisting of nitric acid (HNO_3), sulfuric acid (H_2SO_4), and perchloric acid ($HClO_4$) in a ratio of 5:1:0.5 (Zafar *et al.* 2010). The sample was heated in the acid solution on a hot plate at 85 to 100 °C until digestion was complete, as evidenced by the emergence of white fumes from the flask. Subsequently, a few drops of distilled water were added, and the mixture was permitted to cool. The digested samples were transferred to 50-mL volumetric flasks, the volume was adjusted to 50 mL with distilled water, and the extract was filtered using Whatman No. 42 filter paper, with the filtrate collected in plastic bottles for analysis. The solutions were analyzed for the elements of interest using an atomic absorption spectrometer (AAS). The percentage of various elements in these samples were determined using the corresponding standard calibration curves generated from standard solutions of the heavy metal including lead (Pb), cadmium (Cd), and arsenic (As) (Zafar *et al.* 2010).

Soil Properties Analysis

The soil properties and heavy metal contents before and after the two-year experiment. Soil samples were collected before and after the experimental period to assess the dynamic changes induced by the fly ash-derived soil conditioner. Sampling was conducted at a depth of 0 to 30 cm. In each experimental sub-plot, five random soil cores were collected and homogenized to form a single composite sample for laboratory analysis. The collected soil samples were then subjected to comprehensive analysis to determine their properties and total heavy metal content.

Physicochemical properties and nutrient analysis

The following chemical properties and heavy metal contents were determined using established methods: Soil texture was determined by the standard method. Soil pH was measured using a pH meter in a 1:1 soil:water suspension. Organic matter (OM) content was determined using the Walkley and Black wet oxidation method (Walkley and Black 1934). Available phosphorus (Available P) was analyzed using the Bray II method (Bray 1945). Exchangeable cations potassium (Exch. K) were extracted and determined according to the Pratt method (Pratt 1965). Cation exchange capacity (CEC) was analyzed according to the method described by IITA (1979). Base Saturation (BS) was calculated as the percentage ratio of the sum of total exchangeable basic cations (in milliequivalents per 100 grams of soil) to the measured CEC value, multiplied by 100.

The total content of heavy metals, including Pb, Cd, and As, was analyzed in the soil. The digestion and analysis of the total heavy metals were conducted following the procedures outlined in the *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods* (SW-846) (Chen and Cutright 2001).

Statistical Analysis

All data were analyzed using analysis of variance (ANOVA) suitable for a randomized complete block design (RCBD). The Least Significant Difference (LSD) at the 5% level was employed to determine significant statistical differences. The statistical analysis was performed using Statistical Package for Social Sciences (IBM SPSS Statistics version 31, Chicago, IL, USA).

RESULTS

Rainfall Distribution

The precipitation distribution was acquired from the Thai Meteorological Department in Bangkok, Thailand. The experiment was conducted over a two-year duration, from June 2017 to June 2019. Following cultivation in June 2017, rainfall increased in July and August 2017, measuring 234.2 mm and 275.4 mm, respectively. Subsequently, precipitation diminished, falling to 38.2 mm in September and attaining its nadir from December 2017 to February 2018, coinciding with the dry season (Fig. 1). In March 2018, precipitation commenced to rise again, reaching its zenith in May 2018 at 176.0 mm. In the second year, there was a gradual decline in precipitation, succeeded by an increase in September 2018. This was followed by another dry season from December 2018 to February 2019, particularly in January 2019, which was marked by a total absence of rainfall (0.0 mm). Precipitation commenced to rise again in March 2019, reaching a zenith in May 2019 (171.6 mm), and thereafter diminished. Fig. 1.

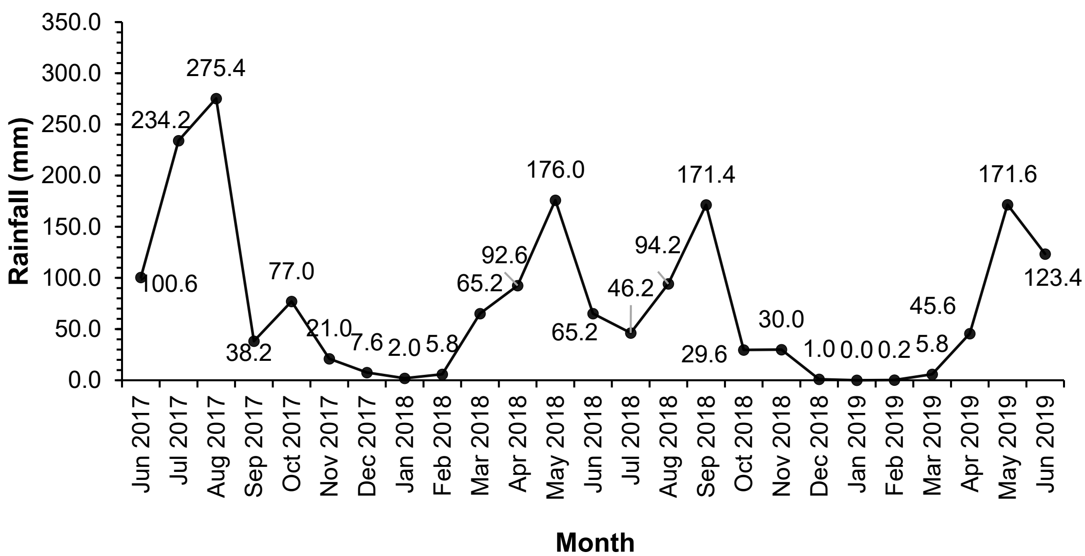

Fig. 1. Mean monthly rainfall from June 2017 to June 2019 at Buriram Livestock Research and Testing Station, Buriram province, Thailand

Plant Height

Table 2 presents the heights of Napier grass for all treatments and harvesting cycles. Results indicated that treatments incorporating fly ash, specifically FF1563, FF3125, FF6250, and FF12500, consistently resulted in superior plant growth. For instance, one and two months post-planting in the initial harvesting cycle, the applications of FF1563, DF, and MF exhibited significantly greater plant heights compared to the control (63.3 and 226.9 cm, respectively). No notable variations in the height of Napier grass were detected three months post-planting.

During the second harvesting cycle, no notable differences in plant height were observed at one- and three-months post-harvest; however, two months after harvesting, the plant height for the FF1563 application (281.7 cm) was significantly greater than that of the DF application (255.4 cm) and the control (236.5 cm). One and two months subsequent to the third harvesting cycle, the applications of FF3125, FF1563, and MF exhibited markedly greater plant heights compared to the control group. The application of FF3125 yielded the greatest plant height among all treatments three months post-harvest. At 1- and 3-months post-harvest of the 4th cycle, no significant differences were observed in the height of Napier grass across different levels of soil conditioner. Nonetheless, MF, FF1563, and FF3125 exhibited markedly increased plant height relative to measurements recorded two months post-harvest. During the fifth and sixth harvesting cycles, the control exhibited markedly reduced plant heights relative to all treatments at one-, two-, and three-months post-harvest (Fig. 2). During the seventh cycle, the applications of FF12500, FF6250, and DF exhibited markedly superior plant heights compared to FF1563 one-month post-harvest (Fig. 2).

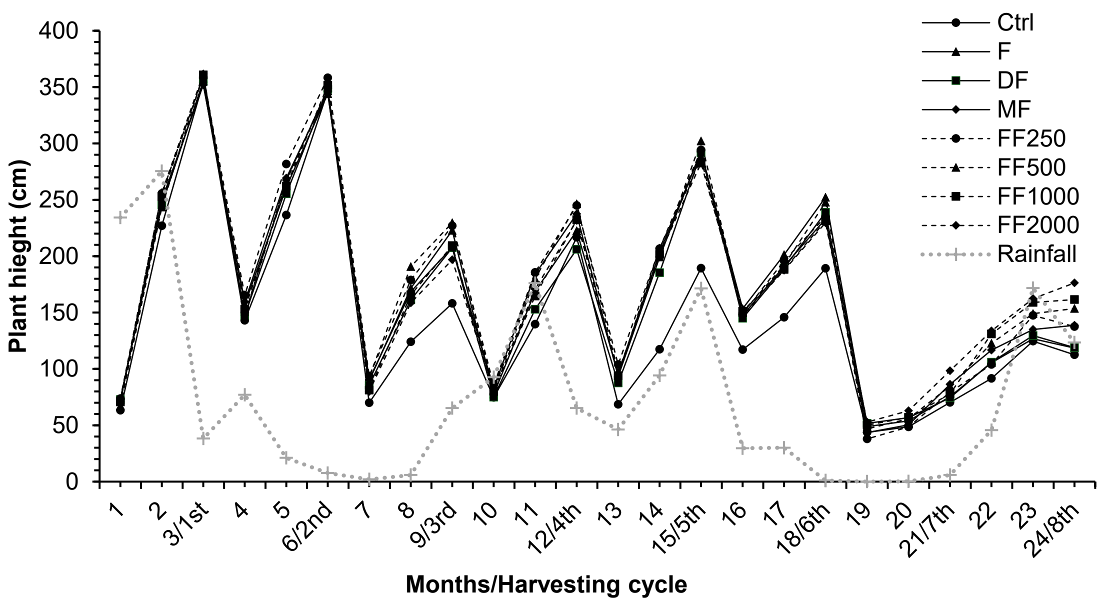

Fig. 2. Plant height of Napier grass (*Pennisetum purpureum*) before each harvesting cycle during 2017 to 2019

At two months post-harvest, the plant height resulting from the FF12500 application was the highest when compared to FF1563, MF applications, and the control, and it also surpassed the plant heights of FF6250, DF, F applications, and the control at three months post-harvest. During the 8th cycle, the applications of FF12500 and FF6250 resulted in markedly greater plant heights compared to FF1563, DF, F, and the control one-month post-harvest. Additionally, the FF12500 application exhibited superior plant height relative to the DF, F applications, and the control at both two- and three-months post-harvest (Fig. 2).

Table 2. Plant Height (cm) of Napier Grass (*Pennisetum purpureum*) Influenced by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Treatment	Months After Planting/Harvesting											
	1st harvesting cycle			2nd harvesting cycle			3rd harvesting cycle			4th harvesting cycle		
	1	2	3	1	2	3	1	2	3	1	2	3
Ctrl	63.3 b	226.9 b	354.3	143.1	236.5 c	346.3	69.9 b	124.0 b	158.1 b	74.7	139.6 b	216.7
F	72.4 ab	245.8 a	355.0	157.0	261.1 abc	344.2	89.4 ab	171.6 ab	222.9 ab	77.4	168.8 ab	222.5
DF	72.8 a	245.6 a	355.1	147.1	255.4 bc	348.0	85.4 ab	161.2 ab	207.5 ab	74.9	152.9 ab	206.1
MF	72.6 a	249.8 a	352.0	159.4	269.3 ab	346.4	90.7 a	168.5 ab	207.9 ab	82.9	184.0 a	237.5
FF1563	73.6 a	255.6 a	358.9	165.3	281.7 a	358.3	93.7 a	178.8 a	226.9 ab	85.6	185.7 a	245.0
FF3125	67.1 ab	243.6 a	361.3	146.5	266.8 ab	346.6	92.8 a	190.7 a	229.6 a	80.7	179.9 a	246.4
FF6250	70.7 ab	252.6 a	360.8	152.8	262.2 ab	351.6	81.2 ab	165.6 ab	209.3 ab	80.0	164.6 ab	232.3
FF12500	70.7 ab	256.3 a	361.7	147.8	267.6 ab	348.4	79.9 ab	158.5ab	196.9 ab	80.7	170.7 ab	231.7
F-test	*	*	ns	ns	**	ns	*	*	**	ns	*	ns
Treatment	Months After Planting/Harvesting											
	5th harvesting cycle			6th harvesting cycle			7th harvesting cycle			8th harvesting cycle		
	1	2	3	1	2	3	1	2	3	1	2	3
Ctrl	68.6 b	117.4 b	189.4 b	117.1 b	145.8 b	189.2 b	43.7 ab	48.6 b	70.3 b	91.5 c	124.6 c	112.5 c
F	95.7 a	203.2 a	292.4 a	153.4 a	201.2 a	252.2 a	48.8 ab	53.9 ab	75.3 b	105.4 b	126.7 c	118.5 bc
DF	87.6 a	185.4 a	291.7 a	149.9 a	189.3 a	238.9 a	51.7 a	56.8 ab	74.3 b	105.8 b	129.6 bc	119.0 bc
MF	93.2 a	199.2 a	293.5 a	147.3 a	191.1 a	233.1 a	43.5 ab	50.3 b	86.3 ab	116.7 ab	134.9 abc	138.6 abc
FF1563	103.9 a	206.7 a	294.3 a	148.8 a	195.8 a	235.0 a	37.9 b	48.5 b	79.3 ab	103.9 bc	147.5 abc	137.5 abc
FF3125	97.1 a	199.3 a	302.2 a	149.9 a	192.1 a	247.8 a	46.8 ab	55.7 ab	84.7 ab	122.6 ab	149.0 abc	153.6 abc
FF6250	94.0 a	201.5 a	282.6 a	151.1 a	188.2 a	231.4 a	50.1 a	57.1 ab	77.7 b	131.0 a	159.0 ab	161.5 ab
FF12500	94.6 a	207.1 a	286.2 a	147.2 a	187.5 a	229.7 a	52.8 a	62.9 a	98.3 a	133.7 a	162.4 a	176.3 a
F-test	*	**	**	*	**	**	**	**	*	**	**	**

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.05$

Number of Tillers (Number of Tiller/Clump)

The tiller counts of Napier grass for all treatments and harvesting cycles are displayed in Table 3. One month post-planting, the initial harvest revealed no notable variations in the tiller counts of Napier grass across different soil conditioner levels. In two months, the applications of FF1563, FF3125, FF6250, and FF12500 demonstrated a higher number of tillers than the control (9.9 tillers/clump). No significant differences were observed among the treatments at three months. During the second harvest cycle, the application of FF1563 resulted in the highest number of tillers at all three months post-cutting, whereas the application of DF exhibited the lowest numbers at one and two months. Both NPK fertilizer applications and the control exhibited significantly reduced tiller counts at three months.

One month post the third harvest, the application of FF1563 exhibited a significantly greater number of tillers compared to the control, while the application of FF12500 demonstrated a significantly higher number of tillers than the applications of FF3125, MF, and NPK fertilizer (F) at the two-month mark. No substantial differences were noted at three months post-intervention. During the fourth harvest, the application of FF12500 consistently resulted in a greater number of tillers compared to the DF application at one, two, and three months. One month post-harvesting, both DF and F applications exhibited significantly reduced tiller numbers compared to the FF12500 application. No significant differences in tiller numbers were observed one month post-cutting during the fifth harvest. At two months, the control exhibited fewer tillers than the MF application and all other treatments, and this pattern persisted at three months post-cutting. In the sixth harvest, the applications of FF1563 and F exhibited greater tiller counts than the control group one month after cutting.

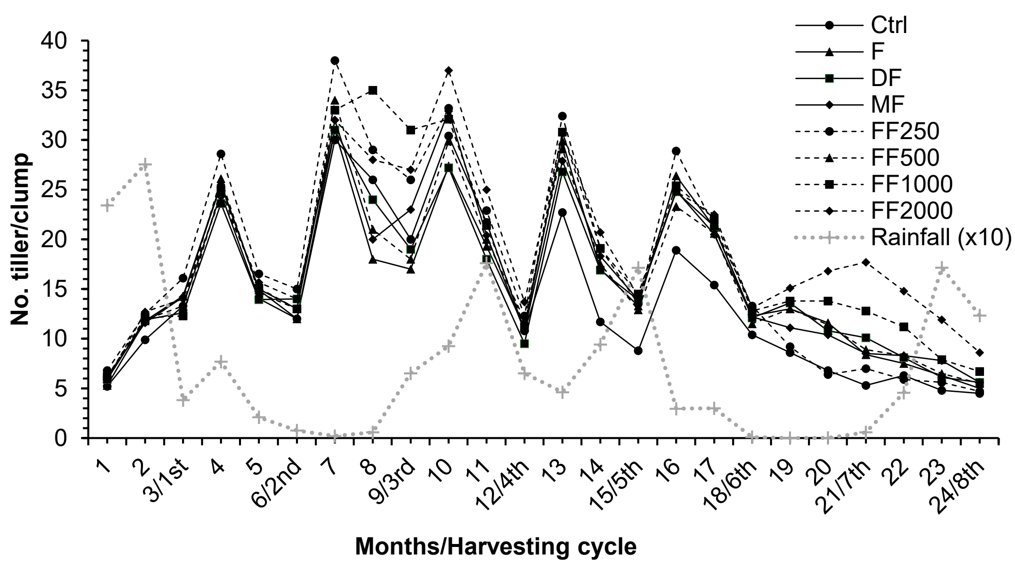

Fig. 3. The number of tiller (no. tiller/clump) of Napier grass (*Pennisetum purpureum*) before each harvesting cycle during 2017 to 2019

The control exhibited markedly fewer tiller numbers than the applications of FF12500, FF6250, FF3125, and DF at two months; however, no significant differences were noted at three months post-harvest.

One month following the seventh harvesting cycle, the applications of FF12500, FF6250, and DF exhibited a markedly higher number of tillers compared to the applications of FF1563 and the control group.

Following a two-month cutting period, the FF12500 application demonstrated a greater number of tillers compared to the FF1563, MF, and control applications, exhibiting the highest tiller count three months post-harvest (Fig. 3). In the eighth harvest, the application of FF12500 consistently demonstrated significantly greater tiller counts than other levels, with the exception of the FF6250 application, at both one- and three-months post-cutting.

Leaf/Stem Ratio

Table 4 presents the leaf/stem ratio for all treatments and harvesting cycles. During the first, second, and seventh harvesting cycles, the leaf/stem ratio of Napier grass exhibited no significant variations among the different levels of soil conditioner. During the third and fifth harvesting cycles, the control demonstrated the highest leaf/stem ratios, recorded at 1.62 and 0.75 respectively, which were statistically distinct from the other treatments (Fig. 4).

The utilization of NPK fertilizer (F) exhibited a markedly superior leaf/stem ratio in comparison to both FF12500 and MF applications during the fourth harvesting cycle. During the sixth harvesting cycle, the control demonstrated a markedly superior leaf/stem ratio in comparison to the treatments of F, MF, FF1563, FF3125, FF6250, and FF12500. During the eighth harvesting cycle, the utilization of DF demonstrated a markedly superior leaf/stem ratio in comparison to both MF and FF1563 applications.

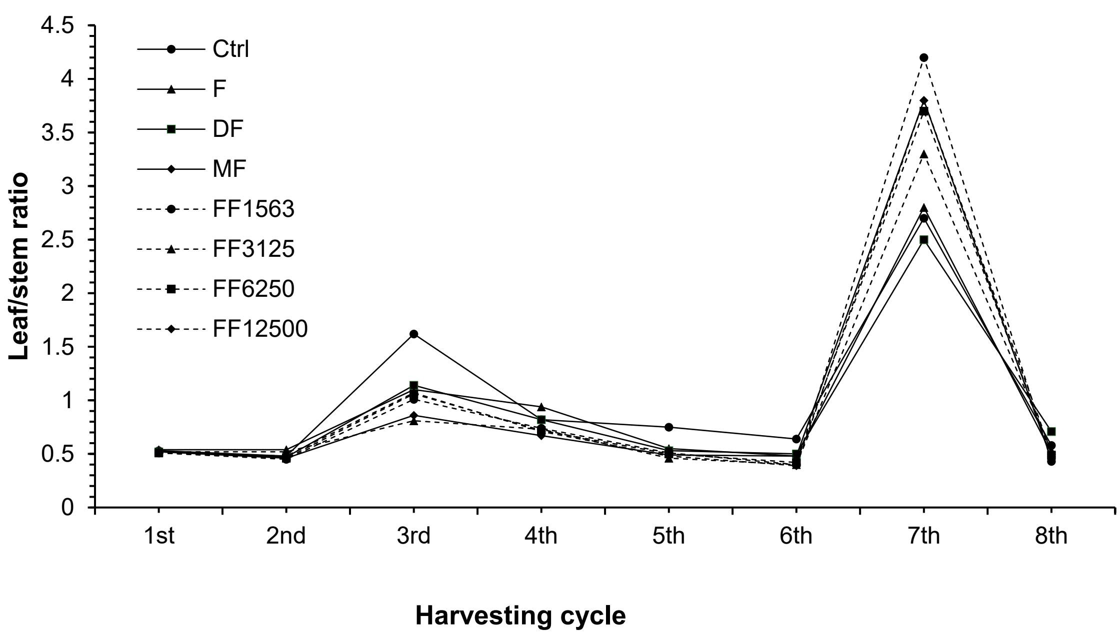

Fig. 4. Leaf/stem ratio of Napier grass (*Pennisetum purpureum*) in each harvesting cycle during 2017 to 2019

Table 3. The Number of Tiller (No. Tiller/clump) of Napier Grass (*Pennisetum purpureum*) Influenced by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Treatment	Months After Planting/Harvesting											
	1st harvesting cycle			2nd harvesting cycle			3rd harvesting cycle			4th harvesting cycle		
	1	2	3	1	2	3	1	2	3	1	2	3
Ctrl	5.2	9.9 b	13.3	24.6 ab	14.0 b	12.0 b	30.0 b	26.0 ab	20.0	30.4 ab	21.7ab	10.8 ab
F	5.3	11.8 ab	14.3	25.6 ab	14.9 ab	12.0 b	31.0 ab	18.0 b	17.0	27.4 b	19.3 ab	11.1 ab
DF	5.9	11.9 ab	12.6	23.6 b	13.9 b	14.0 ab	31.0 ab	24.0 ab	19.0	27.2 b	18.0 b	9.5 b
MF	6.2	11.6 ab	14.2	25.5 ab	15.0 ab	13.0 ab	32.0 ab	20.0 b	23.0	32.9 ab	20.4 ab	10.8 ab
FF1563	6.8	12.5 a	16.1	28.6 a	16.5 a	15.0 a	38.0 a	29.0 ab	26.0	33.2 ab	22.9 ab	12.3 ab
FF3125	6.0	11.9 a	13.3	26.1 ab	14.6 ab	13.0 ab	34.0 ab	21.0 b	18.0	29.9 ab	20.0 ab	11.9 ab
FF6250	6.2	12.1 a	12.3	25.0 ab	15.1 ab	13.0 ab	33.0 ab	35.0 a	31.0	32.1 ab	21.4 ab	11.2 ab
FF12500	5.9	12.7 a	14.0	24.3 ab	15.7 ab	14.0 ab	32.0 ab	28.0 ab	27.0	37.0 a	25.0 a	13.7 a
F-test	ns	*	ns	*	*	*	*	*	ns	*	*	*
Treatment	Months After Planting/Harvesting											
	5th harvesting cycle			6th harvesting cycle			7th harvesting cycle			8th harvesting cycle		
	1	2	3	1	2	3	1	2	3	1	2	3
Ctrl	22.7	11.7 b	8.8 b	18.9 b	15.4 b	10.4	8.6 c	6.8 c	5.3 d	6.3 c	4.8 b	4.5 b
F	29.9	17.0 ab	13.3 a	26.4 a	21.2 ab	12.3	13.0 ab	11.6 abc	8.4 bcd	7.5 bc	6.3 b	5.0 b
DF	26.8	16.9 ab	13.9 a	24.8 ab	21.3 a	12.1	13.6 a	10.8 abc	10.1 bc	8.1 bc	6.1 b	5.6 b
MF	27.9	18.3 a	13.9 a	24.9 ab	20.5 ab	12.2	11.1 abc	10.4 bc	8.5 bcd	8.3 bc	7.8 b	5.6 b
FF1563	32.4	19.1 a	13.5 a	28.9 a	21.3 a	13.3	9.2 bc	6.4 c	7.0 cd	5.9 c	5.6 b	4.7 b
FF3125	29.1	17.5 a	12.9 a	23.3 ab	20.6 ab	11.5	13.0 ab	11.4 abc	8.9 bcd	8.3 bc	6.5 b	5.5 b
FF6250	30.8	19.1 a	14.5 a	25.4 ab	22.1 a	12.8	13.8 a	13.8 ab	12.8 c	11.2 ab	7.9 b	6.7 ab
FF12500	30.7	20.7 a	14.3 a	24.8 ab	22.5 a	13.1	15.1 a	16.8 a	17.7 a	14.8 a	11.9 a	8.6 a
F-test	ns	*	*	*	*	ns	*	**	**	**	**	**

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.0$

Table 4. Leaf/Stem Ratio of Napier Grass (*Pennisetum purpureum*) Influenced by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Treatment	1st Harvesting Cycle	2nd Harvesting Cycle	3rd Harvesting Cycle	4th Harvesting Cycle
Ctrl	0.53	0.48	1.62 a	0.82 ab
F	0.54	0.54	1.10 b	0.94 a
DF	0.52	0.47	1.14 b	0.82 ab
MF	0.52	0.46	0.86 b	0.67 b
FF1563	0.51	0.45	1.01 b	0.74 ab
FF3125	0.52	0.52	0.81 b	0.73 ab
FF6250	0.51	0.46	1.06 b	0.72 ab
FF12500	0.52	0.48	1.07 b	0.71 b
F-test	ns	ns	**	*
Treatment	5th Harvesting Cycle	6th Harvesting Cycle	7th Harvesting Cycle	8th Harvesting Cycle
Ctrl	0.75 a	0.64 a	2.7	0.58 ab
F	0.55 b	0.48 b	2.8	0.51 ab
DF	0.53 b	0.50 ab	2.5	0.71 a
MF	0.49 b	0.48 b	3.8	0.45 b
FF1563	0.51 b	0.40 b	4.2	0.43 b
FF3125	0.46 b	0.40 b	3.3	0.53 ab
FF6250	0.50 b	0.42 b	3.7	0.49 ab
FF12500	0.48 b	0.39 b	3.8	0.51 ab
F-test	*	**	ns	*

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.05$

Table 5. Fresh and Dry Weight Yield (kg/ha) of Napier Grass (*Pennisetum purpureum*) Influenced by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Treatment	Fresh Weight Yield (kg/ha)							
	1st harvesting	2nd harvesting	3rd harvesting	4th harvesting	5th harvesting	6th harvesting	7th harvesting	8th harvesting
Ctrl	50,014 c	28,770 b	10,089 b	7,686 b	5,108 b	4,469 b	502.8 c	2,417 e
F	55,136 bc	38,347 ab	24,070 a	16,456 ab	28,139 a	13,497 a	958.3 bc	2,882 de
DF	59,867 abc	34,933 ab	18,400 ab	12,828 ab	27,411 a	10,867 a	1,130.6 bc	3,178 de
MF	60,870 abc	40,436 ab	21,170 ab	15,719 ab	36,136 a	11,900 a	1,325.0 bc	4,713 cd
FF1563	64,858 ab	53,025 a	27,197 a	22,039 a	37,608 a	12,331 a	686.1 c	4,648 cd
FF3125	63,719 abc	45,578 ab	25,183 a	16,408 ab	33,253 a	12,694 a	1,372.2 bc	5,997 bc
FF6250	63,086 abc	40,619 ab	20,092 ab	15,075 ab	32,739 a	12,319 a	1,900.0 b	7,744 b
FF12500	69,367 a	48,625 ab	19,431 ab	22,314 a	33,975 a	14,258 a	3,516.7 a	10,849 a
F-test	**	**	*	*	**	**	**	**
Treatment	Dry Weight Yield (kg/ha)							
	1st harvesting	2nd harvesting	3rd harvesting	4th harvesting	5th harvesting	6th harvesting	7th harvesting	8th harvesting
Ctrl	10,832 b	8,544 ab	2,092 b	1,900 b	1,830 b	1,042 b	77.2 b	519 c
F	12,248 ab	6,171 b	4,574 ab	4,160 ab	6,214 a	3,789 a	155.1 b	606 c
DF	13,283 ab	7,659 ab	3,503 ab	2,902 ab	5,499 a	3,265 a	164.8 b	718 bc
MF	13,836 ab	11,160 ab	3,842 ab	3,915 ab	7,262 a	3,163 a	169.6 b	977 bc
FF1563	13,926 ab	10,937 ab	4,839 a	5,382 a	8,025 a	3,556 a	117.7 b	1,142 bc
FF3125	14,167 ab	11,934 a	4,690 a	4,056 ab	7,015 a	3,176 a	187.0 b	1,362 bc
FF6250	13,743 ab	11,133 ab	3,574 ab	3,609 ab	6,480 a	3,787 a	282.4 b	1,497 b
FF12500	14,846 a	9,474 ab	3,625 ab	5,183 a	7,248 a	3,421 a	699.1 a	2,670 a
F-test	**	**	*	*	*	**	**	**

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.05$

Fresh and Dry Weight Yield

Table 5 presents the fresh and dry weight yields for all treatments and harvesting cycles. During the initial harvesting cycle, the highest soil conditioner level (FF12500) produced a markedly superior fresh weight compared to both the NPK fertilizer application (F) and the control, with weights of 55,136 kg/ha and 50,014 kg/ha, respectively. During the second harvesting cycle, the application of FF1563 demonstrated a markedly greater fresh weight yield compared to the control. During the third harvesting cycle, the applications of FF1563 and FF3125, in conjunction with the NPK fertilizer (F), exhibited markedly superior fresh weight yields relative to the control group. In the fourth harvesting cycle, the applications of FF12500 and FF1563 demonstrated markedly higher fresh weights compared to the control group. During the fifth and sixth harvesting cycles, the control exhibited the lowest fresh weight yield, markedly inferior to all treatments. Moreover, the utilization of FF12500 exhibited a markedly superior fresh weight yield compared to alternative soil conditioner levels during the 7th and 8th harvesting cycles (Fig. 5).

The maximum application level of the soil conditioner (FF12500) exhibited a markedly higher dry weight yield compared to the control during the 1st, 7th, and 8th harvesting cycles. During the second harvesting cycle, the application of FF3125 resulted in a markedly greater dry weight yield compared to the application of NPK fertilizer (F). During the third harvesting cycle, both the FF1563 and FF3125 applications exhibited markedly superior dry weight yields relative to the control group. During the fourth harvesting cycle, the applications of FF12500 and FF1563 yielded markedly greater dry weight compared to the control group. In the fifth and sixth cycles, all treatments exhibited significantly greater dry weight yields compared to the control (Fig. 5).

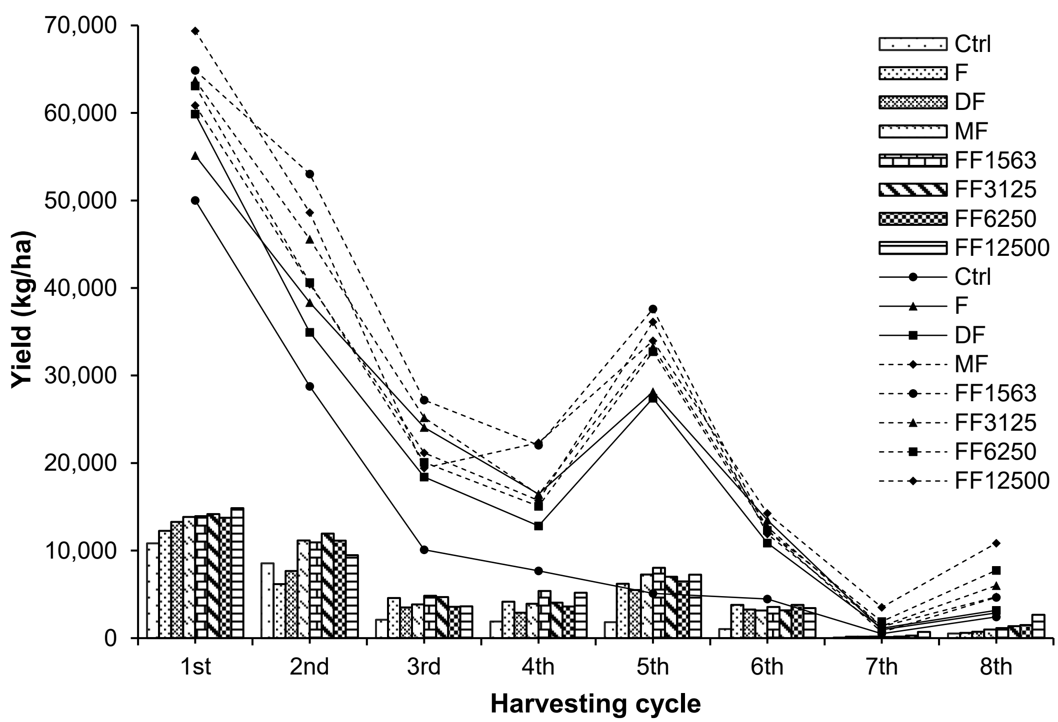

Fig. 5. Yield of Napier grass (*Pennisetum purpureum*) in each harvesting cycle during 2017 to 2019, line plot indicated fresh weight (kg/ha) and column plot indicated dry weight (kg/ha)

Elemental Analysis

The concentrations of heavy metals, including Pb, Cd, and As, in Napier grass are illustrated in Table 6. The application of FF3125 demonstrated a markedly elevated concentration of Pb (0.46 mg/kg) compared to the applications of FF6250 (0.24 mg/kg), FF12500 (0.20 mg/kg), and the control group. An analysis of Cd content (ranging from 0.01 to 0.02 mg/kg) and As content (ranging from 0.03 to 0.04 mg/kg) indicated no significant differences among the various levels of soil conditioners.

Table 6. Heavy Metal Content in Final Harvesting Cycle of Napier Grass (*Pennisetum purpureum*) Influenced by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Treatment	Heavy Metal Content (mg/kg)		
	Pb	Cd	As
Ctrl	0.23 b	0.01	0.03
F	0.28 ab	0.01	0.03
DF	0.27 ab	0.02	0.03
MF	0.29 ab	0.01	0.03
FF1563	0.26 ab	0.02	0.04
FF3125	0.46 a	0.02	0.03
FF6250	0.24 b	0.02	0.04
FF12500	0.20 b	0.01	0.04
F-test	*	ns	ns

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.05$.

Table 7. Soil pH, Organic matter (OM), Available Phosphorus (Avai. P), Exchangeable Potassium (Exch. K), Cation Exchange Capacity (CEC), Base Saturation (BS) and Heavy Metal Contents of Soils Before and After the Application by Different Levels of Soil Conditioner Derived from Fly Ash During 2017 to 2019

Before Experiment									
	pH	OM (%)	Available P (mg/kg)	Exch. K (mg/kg)	CEC (cmol/kg)	BS (%)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
	5.9	0.60	18.70	54.00	1.12	41.00	1.23	nd	nd
After Experiment									
	pH	OM (%)	Available P (mg/kg)	Exch. K (mg/kg)	CEC (cmol/kg)	BS (%)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Control	5.9 bcd	0.77	3.98 b	17.14	1.57	57.80 cd	0.41	nd	nd
F	5.6 d	0.90	9.82 b	24.37	1.62	56.04 d	0.74	nd	0.01
MF	5.9 bcd	0.72	8.53 b	25.32	1.87	57.27 ab	0.41	nd	nd
DF	6.3 cd	0.78	14.06 b	19.19	1.69	75.12 cd	0.74	nd	nd
FF1563	6.1 bcd	0.76	14.92 b	43.62	1.80	61.18 bcd	0.58	nd	nd
FF3125	6.8 b	0.76	28.33 b	29.43	1.36	65.83 bcd	0.50	nd	nd
FF6250	6.7 bc	0.71	35.36 b	30.34	1.61	71.00 bc	0.66	nd	0.01
FF12500	7.8 a	0.74	118.94 a	60.47	1.07	87.06 a	0.82	nd	0.01
F-test	**	ns	*	ns	ns	**	ns	-	-

*, ** = significant differences at the $p < 0.05$ and $p < 0.01$, respectively; ns = no significant difference; means with the same lowercase letter in the same column are not significantly different at $p < 0.05$
nd = Non-detected

Soil Properties Analysis

Table 7 presents the soil pH, which showed highly significant increases. It shifted from an initial pH of 5.9 to a maximum of 7.8 in the FF12500, confirming the fly ash's high efficiency as a liming agent. BS also increased highly significantly, rising from an initial value of 41.0% to a peak of 87.1% in the FF12500, validating the improvement in the soil's chemical fertility available P content increased significantly. It soared from the initial concentration of 18.7 mg/kg to 118.9 mg/kg in the FF12500 treatment. Although not statistically significant overall, the highest final Exch. K content was recorded in the FF12500 (60.47 mg/kg). Cd and As contents were not detected in any sample (initial or final). Pb content in most treated soils was lower than the initial concentration of 1.23 mg/kg.

DISCUSSION

Fly ash has several characteristics that can substantially enhance agricultural soil quality. The response of Napier grass to the application of fly ash as a soil conditioner demonstrated a consistent improvement in growth compared with the control across all application levels. This finding aligns with previous studies reporting that the incorporation of 20 to 30% fly ash into soil improved both growth and yield in wheat, with similar responses observed in a wide range of plant species, including *Cynodon dactylon*, green gram, *Pisum sativum*, *Mentha citrata*, *Daucus carota*, *Brassica juncea*, *Raphanus sativus*, and *Zea mays* (Bharia *et al*. 2000; Pathan *et al*. 2003; Dhindsa *et al*. 2016; Shakeel *et al*. 2019; Shakeel *et al*. 2021; Ansari *et al*. 2022; Rafiullah *et al*. 2022). These positive responses are attributed to the presence of essential macro- and micronutrients in fly ash, including silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), copper (Cu), and other trace elements critical for plant growth (Ahmed *et al.* 2021). In addition, fly ash is predominantly alkaline; its incorporation into soil aids in regulating soil pH, thereby creating a more favorable environment for plant growth. Consequently, Napier grass grown in fly ash–amended soil exhibited greater resilience and more vigorous growth than the control.

The experiment was conducted under rain-fed conditions, which resulted in pronounced fluctuations in growth and yield parameters across the eight harvesting cycles. Rainfall data indicated alternating periods of high precipitation and severe drought, which largely explain the observed temporal variations in plant performance. Following the second and sixth harvesting cycles, reduced rainfall contributed to a decline in plant height prior to the third and seventh harvests, respectively (Fig. 1). Concurrently, an increase in the leaf/stem ratio indicated an adaptive response to drought stress, characterized by reduced stem elongation and a consequent reduction in yield (Fig. 5). Yield declines during these cycles were consistently observed across all treatments, underscoring the strong dependence of plant growth on water availability under rain-fed conditions. Nevertheless, Napier grass receiving fly ash treatments consistently exhibited greater height and yield than the control (Tables 1 and 4), suggesting that fly ash significantly enhanced soil water retention and moisture conservation capacity (Panda and Biswal 2018).

Prior to the fifth harvesting cycle, increased precipitation led to a recovery in plant height (Fig. 1) and improvements in both fresh and dry biomass yields (Fig. 5). Despite this recovery, the control treatment consistently exhibited the lowest plant height throughout the study period (Table 1 and Fig. 2). This response may be attributed to more pronounced nutrient leaching from the control soil compared with soils amended with fertilizers and fly ash, particularly under conditions of elevated soil moisture. During this period, the leaf/stem ratio decreased due to enhanced stem growth (Fig. 4). The control treatment exhibited the highest leaf/stem ratio among all treatments (Table 3 and Fig. 4), indicating relatively limited stem development. These findings suggest that nutrients supplied by fly ash preferentially stimulated stem growth rather than leaf expansion, a response that is particularly desirable for Napier grass grown for biomass production (Smith and Jones 2020).

Enhanced tillering represents an important adaptive trait that enables plants to tolerate frequent defoliation by restoring photosynthetic capacity and maintaining basal area. Increased tiller density also reduces apical dominance and promotes basal shoot development (Ernawati *et al*. 2023). Pronounced tillering was observed prior to the third and seventh harvesting cycles across all treatments, with the strongest response occurring in plots receiving higher fly ash application levels, particularly FF12500 during the seventh harvest (Fig. 3). Following drought periods, subsequent increases in precipitation (Fig. 1) coincided with reduced plant height, reflecting substantial investment in basal shoot growth rather than vertical elongation.

Throughout the two-year experimental period, the control consistently exhibited the lowest plant height and biomass yield. This pattern suggests that the physicochemical improvements induced by fly ash application mitigated environmental stress, particularly water limitation. The enhanced soil water retention and moisture preservation associated with fly ash amendments likely buffered plants against the most severe impacts of dry seasons, enabling treated plots to maintain superior performance relative to the control, especially during the fifth and sixth harvest cycles. The pronounced yield decline observed in the control may also be attributed to increased leaching of nutrients such as N and K during periods of heavy rainfall, an effect that was alleviated in fly ash–amended soils due to improved nutrient retention.

The consistently lower leaf/stem ratio observed in fly ash treatments (Fig. 4) further indicates that fly ash promotes stem biomass accumulation over leaf expansion. This response is likely associated with the chemical composition of the fly ash (Table 1), particularly its high Si and K contents. Silicon enhances mechanical strength and structural integrity in grasses by reinforcing cell walls, thereby promoting thicker and heavier stems. Potassium plays a crucial role in plant water regulation and assimilates partitioning toward structural biomass in high-yielding perennial crops, collectively favoring stem-dominated biomass production.

The yield enhancement observed in Napier grass is consistent with responses reported for other high-biomass crops, such as sugarcane and maize, in which fly ash conditioners improved growth through enhanced soil structure and nutrient supply. However, the rapid growth rate and strong tillering capacity of Napier grass make it particularly responsive to the rapid liming effect and nutrient release associated with fly ash application. Notably, this study demonstrated that relatively low application levels of fly ash are sufficient to achieve significant agronomic benefits compared with those typically applied in cropping systems, suggesting strong economic potential for biomass energy production systems.

Over the two-year period, fly ash application induced significant and beneficial changes in soil physicochemical properties and heavy metal behavior, which are critical for the sustainable use of Napier grass as a biomass crop. In particular, soil pH increased significantly with fly ash application, with the highest level (FF12500) raising pH from an initially mildly acidic value of 5.9 to a maximum of 7.8. This pronounced shift toward slightly alkaline conditions confirms the strong liming capacity of fly ash, which plays a key role in improving soil fertility and mitigating Al toxicity in acidic soils.

This liming effect was directly reflected in base saturation (BS), which increased substantially across all treatments. BS increased from an initial value of 41.0% to a maximum of 87.1% under the FF12500 treatment, indicating the effective replacement of acidic cations (H^+ and Al^{3+}) on the soil exchange complex by base cations (Ca^{2+}, Mg^{2+}, and K^+) supplied by fly ash. These changes significantly enhanced overall soil chemical fertility and buffering capacity. In addition, available phosphorus (available P) increased markedly, rising from 18.7 to 118.9 mg/kg in the FF12500 treatment. This increase highlights the dual role of fly ash as both a direct source of phosphorus and an agent that creates a near-neutral pH environment favorable for phosphorus solubility while reducing fixation under strongly acidic or alkaline conditions. A similar trend was observed for exchangeable potassium (Exch. K), which increased from 54.0 to 60.5 mg/kg under FF12500, confirming fly ash as a supplementary potassium source.

Napier grass is a fast-growing species with a robust root system that enables tolerance to elevated heavy metal concentrations and confers potential for phyto-stabilization. Previous studies have shown that Napier grass can absorb and translocate heavy metals within plant tissues, although accumulation patterns depend on the specific metal and growth substrate (Couselo *et al*. 2012; Gajaje *et al.* 2024). Analysis of the fly ash used in this study indicated non-detectable concentrations of Pb and Cd (Table 1). Therefore, the Pb and Cd accumulated in Napier grass biomass originated exclusively from native soil sources, where the initial Pb concentration was 1.23 mg/kg. Importantly, no significant differences in Cd and As concentrations were observed across fly ash application levels (Table 5), indicating that fly ash application did not exacerbate accumulation of these metals.

High application levels of fly ash (FF6250 and FF12500) resulted in a significant reduction in the exchangeable (mobile) fraction of native soil Pb, with final Pb concentrations in treated soils falling below initial levels. This finding confirms that the alkalinity induced by fly ash promoted physicochemical immobilization of Pb in the soil. Two distinct phases of Pb uptake in Napier grass were identified. At the low application level (FF3125), a slight increase in Pb uptake likely reflected a transient shift in metal mobility due to intermediate pH conditions and insufficient competition from Ca^{2+}. In contrast, higher application levels markedly increased soil pH, favoring Pb immobilization through precipitation as low-solubility hydroxides ($Pb(OH)_2$) and carbonates ($PbCO_3$). This process substantially reduced Pb bioavailability, resulting in the lowest Pb concentrations in harvested biomass.

Napier grass, as cultivated in this study, is intended primarily for biomass energy production. The results demonstrate that fly ash is an effective soil conditioner, capable of significantly enhancing growth and biomass yield while simultaneously reducing the bioavailability of native soil heavy metals at optimal application levels. Crucially, Pb concentrations in harvested Napier grass remained well below the maximum permissible limit (<10 mg/kg) for energy crops (Oberle *et al*. 2010), confirming that appropriate optimization of fly ash application levels can improve soil fertility and biomass productivity while ensuring environmental safety and end-use suitability.

CONCLUSIONS

This study confirms the high efficacy of fly ash as a soil conditioner for enhancing the growth and yield performance of Napier grass in rain-fed conditions. The key findings and practical implications are summarized as follows:

1. The intermediate fly ash level (FF6250) demonstrated the best balance, resulting in a substantial and sustained increase in biomass yield over the two-year period, establishing it as the optimal treatment.
2. Fly ash application altered nutrient partitioning, favoring stem growth over leaf expansion. This effect is driven by the release of key elements such as silicon and potassium, leading to the production of high structural biomass suitable for high-volume forage or energy production.
3. The high application levels (FF6250 and FF12500) were highly effective in increasing soil alkalinity and thereby immobilizing Pb in the native soil, reducing its uptake by the grass to levels safe for its intended end-use as energy crop.
4. The substantial increase in biomass yield achieved with the low-cost fly ash waste material suggests that this application is a highly cost-effective and sustainable solution for both agricultural productivity enhancement and industrial waste management.
5. Future studies should explore the co-application of fly ash with other materials, such as biochar or activated carbon, to further enhance the long-term stabilization and immobilization of native soil heavy metals.

ACKNOWLEDGMENTS

The authors extend their sincere gratitude to the Kasetsart Agricultural and Agro-Industrial Product Improvement Institute (KAPI) for providing financial support through the Fly Ash Soil Conditioner Project. We also deeply appreciate the Department of Livestock Development (DLD), Thailand, for granting access to their farm plots, which were essential for the successful completion of this research.

REFERENCES CITED

Ahmad, G., Khan, A. A., and Mohamed, H. I. (2021). "Impact of the low and high concentrations of fly ash amended soil on growth, physiological response and yield of pumpkin (*Cucurbita moschata* Duch. Ex Poiret L.)," *Environmental Science and Pollution Research* 28(14), 17068-17083. https://doi.org/10.1007/s11356-020-12029-8

Ansari, M. S., Ahmad, G., Khan, A. A., Mohamed, H. I., and Elhakem, A. (2022). "Coal fly ash and nitrogen application as eco-friendly approaches for modulating the growth, yield, and biochemical constituents of radish plants," *Saudi Journal of Biological Sciences* 29, article 10330. https://doi.org/10.1016/j.sjbs.2022.103306

Antonkiewicz, J., Kowalewska, A., Mikołajczak, S., Kołodziej B., Bryk, M., Spychaj-Fabisiak, E., Koliopoulos, T., and Babula, J. (2022). "Phytoextraction of heavy metals after application of bottom ash and municipal sewage sludge considering the risk of environmental pollution," *Journal of Environmental Management* 306, article 114517. https://doi.org/10.1016/j.jenvman.2022.114517

Bharti, M., Matte, D. B., Badle, W. P., and Deshmukh, A. (2000). "Effect of fly ash on yield, uptake of nutrients and quality of green grown on versitol," *Journal of Soils and Crops* 10, 122-124.

Bray II, R. H., and Kurtz, L. T. (1945). "Determination of total, organic, and available forms of phosphorus in soils," *Soil Science* 59(1), 39-45. https://doi.org/10.1097/00010694-194501000-00006

Chen, T. B., and Cutright, T. J. (2001). "EDTA and HEDTA effects on Cd, Cr, and Ni uptake by *Helianthus annuus*," *Chemosphere* 45(1), 21-28. https://doi.org/10.1016/S0045-6535(00)00516-0

Couselo, J. L., Corredoira, E., Vieitez, A. M., and Ballester, A. (2012). "Plant tissue culture of fast-growing trees for phytoremediation research," in: *Plant Cell Culture Protocols*, M. L. Víctor, and O. Neftalí (eds.), Springer Nature, Humana Totowa, NJ, USA, pp. 247-263. https://doi.org/10.1007/978-1-61779-818-4_19

Dhindsa, H. S., Sharma, R. D., and Kumar, R. (2016). "Role of fly ash in improving soil physical properties and yield of wheat (*Triticum aestivum*)," *Agricultural Science Digest* 36(2), 97-101. https://doi.org/10.18805/asd.v36i2.10626

Ernawati, A., Abdullah, L., Permana, I. G., and Karti, P. D. M. H. (2023). "Morphological responses, biomass production and nutrient of *Pennisetum purpureum* cv. Pakchong under different planting patterns and harvesting ages," *Biodiversitas* 24(6), 3439-3447. https://doi.org/10.13057/biodiv/d240640

Gajaje, K., Ultra, Jr, V. U., Nwaefuna, A. E., and Zhou, N. (2024). "Phytostabilization of fly ash from a coalmine in Botswana and biovalorisation of the recovered Napier grass (*Pennisetum purpureum* Schumach.)," *International Journal of Phytoremediation* 26(8), 1291-1304. https://doi.org/10.1080/15226514.2024.2313559

Haegele, T., and Arjharn W. (2017). "The effects of cultivation methods and planting season on biomass yield of Napier grass (*Pennisetum purpureum* Schumach.) under rainfed conditions in the northeast region of Thailand," *Field Crops Research* 214, 359-364. https://doi.org/10.1016/j.fcr.2017.09.027

IITA. (1979). *Selected Methods for Soil and Plant Analysis*. Manual Series No. 1, International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. 57 pp.

Jambhulkar, H. P., Shaikh, S. M. S., and Kumar, M. S. (2018). "Fly ash toxicity, emerging issues and possible implications for its exploitation in agriculture; Indian scenario: A review," *Chemosphere* 213, 333-344. https://doi.org/10.1016/j.chemosphere.2018.09.045

Katiyar, D., Singh, A., Malaviya, P., Pant, D., Singh, P., Abraham, G., and Singh, S. K. (2012). "Impact of fly-ash-amended soil on growth and yield of crop plants," *International Journal of Environment and Waste Management* 10, 150-162. https://doi.org/10.1504/IJEWM.2012.048362

Mittra, B. N., Karmakar, S., Swain, D. K., and Ghosh, B. C. (2005). "CCRs-A potential source of soil amendment and a component of integrated plant nutrient supply system," *Fuel* 84, 1447-1451. https://doi.org/10.1016/j.fuel.2004.10.019

Panda, R. B., and Biswal, T. (2018). "Impact of fly ash on soil properties and productivity," *International Journal of Agriculture Environment & Biotechnology* 11(2), 275-283. https://doi.org/10.22161/ijaeb.11.2.14

Pathan, S. M., Aylmore, L. A. G., and Colmer, T. D. (2003). "Soil properties and turf growth on a sandy soil amended with fly ash," *Plant Soil* 256, 103-114. https://doi.org/10.1023/A:1026203113588

Pincam, T., Brix, H., Eller, F. and Jampeetong, A. (2017). "Hybrid Napier grass as a candidate species for bioenergy in plant-based water treatment systems: Interactive effects of nitrogen and water depth," *Aquatic Botany* 138, 82-91. https://doi.org/10.1016/j.aquabot.2017.01.001

Pratt, P. F. (1965). "Potassium," in: *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*, C. A. Black (ed.), American Society of Agronomy, Inc., Madison, WI, pp. 1022-1030.

Rafiullah, A., Leghari, S. K., Kakar, A. U., Gulshan, A. B., Hussain, F., Shah, S. Q., Baloch, A., and Jakrro, M. I. (2022). "Effect of coal fly ash on seedling growth, productivity, biochemical and heavy metals uptake of *Zea mays* L. and soil characteristics in semi-arid and climatic conditions of Quetta Valley," *GU Journal of Phytosciences* 2(2), 119-128. https://doi.org/10.51860/gujp.2022.2.2.0019

Rajiv, G., and Prakash, M. (2012). "Response of black gram to fly ash application," *Plant Archives* 12(1), 253-256.

Shakeel, A., Khan, A. A., Alharby, H. F., Bamagoos, A. A., Tombuloglu, H., and Hakeem, K. R. (2021). "Evaluation of coal fly ash for modulating the plant growth, yield, and antioxidant properties of *Daucus carota* (L.): A sustainable approach to coal waste recycling," *Sustainability* 13(9), article 5116. https://doi.org/10.3390/su13095116

Shakeel, A., Khan, A. A., and Ahmad, G. (2019). "The potential of thermal power plant fly ash to promote the growth of Indian mustard (*Brassica juncea*) in agricultural soils," *SN Applied Sciences* 1, article 375. https://doi.org/10.1007/s42452-019-0404-9

Singbua, P., Treedet, W., Duangthong, P., Seithtanabutara, V., and Suntivarakorn, R. (2017). "Bio-oil production of Napier grass by using rotating cylindrical reactor," *Energy Procedia*,138, 641-645. https://doi.org/10.1016/j.egypro.2017.10.180

Smith, J., and Jones, A. (2020). "The role of stem growth in biomass production of Napier grass (*Pennisetum purpureum*)," *Journal of Agricultural Research* 15(2), 123-134. https://doi.org/10.1234/JAR.2020.15.2.123

Tudsri, S., Jorgensen, S. T., Riddach, P., and Pookpakdi, A. (2002). "Effect of cutting height and dry season closing date on yield and quality of five Napier grass cultivars in Thailand," *Tropical Grasslands* 36(4), 248-252.

Ukwattage, N. L., Ranjith, P. G., and Bouazza, M. (2013). "The use of coal combustion fly ash as a soil amendment in agricultural lands (with comments on its potential to improve food security and sequester carbon)," *Fuel* 109, 400-408. https://doi.org/10.1016/j.fuel.2013.02.016

Walkley, A., and Black, I. A. (1934). "An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method," *Soil science*, 37, 29-38.

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang J. H., Ge, L. Q., Xia, M. S., and Xi, Y. Q. (2015). "A comprehensive review on the applications of coal fly ash," *Earth-Science Reviews* 141, 105-121. https://doi.org/10.1016/j.earscirev.2014.11.016

Yunusa, A. M., Loganathan, P., Nissanka, S. P., Manoharan, V., Burchett, M. D., Skillbeck, C. G., and Eamus, D. (2012). "Application of coal fly ash in agriculture: A strategic perspective," *Critical Reviews in Environmental Science and Technology* 46(6), 559-600. https://doi.org/10.1080/10643389.2010.520236

Zafar, M., Khan, M. A., Ahmad, M., Jan, G., Sultana, S., Ullah, K., Marwat, S. K., Ahmad, F., Jabeen, A., Nazir, A., *et al.* (2010). "Elemental analysis of some medicinal plants used in traditional medicine by atomic absorption spectrophotometer (AAS)," *Journal of Medicinal Plants Research* 4(19), 1987-1990. https://doi.org/10.5897/JMPR10.081

Article submitted: October 16, 2025; Peer review completed: November 22, 2025; Revised version received: December 16, 2025; Accepted: January 9, 2026; Published: January 20, 2026.
DOI: 10.15376/biores.21.1.2080-2100