International Journal of Plant & Soil Science

Volume 37, Issue 9, Page 720-730, 2025; Article no.IJPSS.144311
ISSN: 2320-7035

Effect of Fly Ash and Farmyard Manure on Soil Quality and Groundnut Productivity in an Acidic Soil

Soumyajeet Pradhan [a*], Prasanna Kumar Samant [a], Meenakhi Prusty [a] and Kumbha Karna Rout [a,b]

[a] Department of Soil Science and Agricultural Chemistry, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha 751003, India.
[b] School of Agriculture, DRIEMS University, Cuttack, Odisha 754022, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i95748

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/144311

Original Research Article

Received: 07/07/2025
Accepted: 15/09/2025
Published: 19/09/2025

ABSTRACT

Fly ash (FA), an industrial by-product from coal-based power plants, remains underutilized in Indian agriculture despite its potential as a nutrient-rich soil amendment. A three-year field experiment was conducted in an acidic Inceptisol of coastal Odisha under a rice–groundnut system to evaluate the residual effects of FA in combination with farmyard manure (FYM). Treatments included graded FA doses (10, 20, and 40 t ha^{-1}) applied once to rice, with residual effects assessed in groundnut. Results demonstrated that FA application significantly improved soil organic carbon (up to 160.7%), available P (40.6%), K (49.2%), and sulphur (100.7%) relative to the control. Plant-available silicon (PASi) also increased markedly, reaching 46.98 mg kg^{-1} in the FA40+FYM treatment. Enhanced soil enzyme activities (urease, phosphatases, dehydrogenase, β-glucosidase) indicated improved microbial functioning and nutrient cycling. Groundnut yields responded positively, with pod and

**Corresponding author: E-mail: soumyabbsr16@gmail.com;*

Cite as: *Soumyajeet Pradhan, Prasanna Kumar Samant, Meenakhi Prusty, and Kumbha Karna Rout. 2025. "Effect of Fly Ash and Farmyard Manure on Soil Quality and Groundnut Productivity in an Acidic Soil". International Journal of Plant & Soil Science 37 (9):720-730. https://doi.org/10.9734/ijpss/2025/v37i95748.*

kernel yields highest in the FA40+FYM treatment (1226.5 and 872.3 kg ha⁻¹, respectively), representing substantial gains over control plots. Multivariate analysis revealed strong positive correlations among soil fertility indicators, enzymatic activities, and yield attributes, with FA-amended treatments clustering distinctly from control treatments. These findings confirm that FA, when integrated with FYM and fertilizers, serves as an effective amendment for improving soil health and crop productivity in acidic soils. The study provides critical insights for sustainable FA recycling in agriculture, contributing to food security and environmental management.

Keywords: Residual effect; soil amelioration; farmyard manure; PCA; fly ash; soil enzymes.

1. INTRODUCTION

Fly ash (FA), a fine particulate by-product of coal combustion, poses a significant environmental challenge due to its vast generation from thermal power plants. In India, an estimated 889.66 lakh metric tons (LMT) of FA is produced annually, a figure expected to rise with the country's reliance on low-grade, high-ash coal (NTPC, 2023). Traditionally considered a waste product, FA contains essential plant macro- and micronutrients, and its properties—such as a highly variable pH (4.5–12.0)—are influenced by the source coal and combustion process (Jala and Goyal, 2006; Lal et al., 2012).

Concurrently, agricultural intensification has led to soil degradation, prompting the search for sustainable soil amendments. FA has emerged as a potential candidate to improve soil health by enhancing texture, porosity, and water retention, while supplementing nutrient levels (Ram and Masto, 2014). Its application, particularly in combination with organic amendments like farmyard manure (FYM), can mitigate heavy metal bioavailability and improve nutrient cycling (Kumar et al., 2017; Singh and Pandey, 2013). Despite these benefits and the potential to significantly boost food grain production, FA utilization in Indian agriculture remains below 1% (Down To Earth, 2019).

Most research has focused on the short-term, direct effects of FA on single crops. A critical knowledge gap exists regarding its residual impact within a cropping sequence, where benefits to a first crop may influence a subsequent one. This is particularly relevant for the predominant rice-groundnut system of coastal Odisha, where groundnut is often grown as a residual crop after rice.

To address this, we conducted a three-year field study to evaluate the integrated application of FA and FYM within a rice-groundnut cropping system. Our objectives were to assess the multi-seasonal impact on soil physicochemical properties and microbial activity.

2. MATERIALS AND METHODS

2.1 Experimental Site and Setup

A field experiment was initiated during the 2021 Kharif season (rice, *Oryza sativa* cv. Kalinga Dhan 1204) followed by the 2021–22 Rabi season (groundnut, *Arachis hypogaea* cv. Devi, ICGV 91114) at the Instructional Farm of Odisha University of Agriculture and Technology (OUAT), Bhubaneswar, India (20.2961° N, 85.8245° E; 45 m above mean sea level). The groundnut variety Devi (ICGV 91114) is an early-maturing, drought-tolerant cultivar recommended for cultivation in Odisha (Ghosal and Sarangi, 2020). The experimental site has a subtropical humid climate with an average annual rainfall of 1,250 mm. The soil was classified as slightly acidic with a loamy sand texture. Fly ash (FA) was procured from the National Thermal Power Corporation (NTPC) in Talcher, Odisha. Initial physicochemical characteristics of the soil, FA, and farmyard manure (FYM) are presented in Table 1.

2.2 Experimental Design and Treatments

The experiment was laid out in a randomized block design (RBD) with three replications. Individual plot size was 12 m × 5 m. This study evaluates seven treatments: T1: Absolute control (no inputs), T2: 100% recommended NPK (20:40:40 kg ha⁻¹ N:P_2O_5:K_2O for groundnut), T3: T2 + FYM @ 5 t ha⁻¹ (applied each Kharif season), T4: T3 + FA @ 10 t ha⁻¹, T5: T3 + FA @ 20 t ha⁻¹, T6: T3 + FA @ 40 t ha⁻¹ and T7: T3 + Lime @ 0.2 LR (applied for non-rice crops). The full quantity of FYM and FA, as per treatment specifications, was incorporated once during puddling for the Kharif rice crop. Lime (0.2 Lime Requirement) was applied based on soil test values during land preparation for the Rabi groundnut crop.

Table 1. Physico-chemical of fly ash, FYM and initial soil

Properties	Fly Ash	FYM	Initial Soil	Reference/Method
Sand (%)	90.4	n.d.	83.56	Bouyoucos hydrometer (1962)
Silt (%)	9.4	n.d.	8.5	Bouyoucos hydrometer (1962)
Clay (%)	0.2	n.d.	7.94	Bouyoucos hydrometer (1962)
Bulk density (Mg m^{-3})	1.04	n.d.	1.29	Blake & Hartge (1986)
Particle density (Mg m^{-3})	1.71	n.d.	2.55	Flint & Flint (2002)
Porosity (%)	39.18	n.d.	50.0	Flint & Flint (2002)
Water holding capacity (%)	92.1	n.d.	32.22	Keen-Raczkowski box
pH	6.1	n.d.	5.13	Jackson (1973)
EC (dS m^{-1})	0.18	n.d.	0.19	Jackson (1973)
CEC (cmol(+) kg^{-1})	n.d.	n.d.	3.06	Piper (1950)
Liming potential (%)	8.5	n.d.	n.d.	Woodruff (1948)
C (%)	0.52	21.0	0.49	CHNS analyzer / Walkley & Black (1934)
N (%)	0.05	0.83	n.d.	CHNS analyzer /
P (%)	0.2	0.26	n.d.	Di-acid digestion / Spectrophotometer
K (%)	0.06	0.82	n.d.	Di-acid digestion / Flame photometer
C:N ratio	n.d.	25.6	n.d.	Calculated
Mineralizable N (kg ha^{-1})	n.d.	n.d.	111.26	Subbiah & Asija (1956)
Olsen's P (kg ha^{-1})	n.d.	n.d.	8.16	Olsen et al. (1954)
Available K (kg ha^{-1})	n.d.	n.d.	96.85	Jackson, 1973
Available S (kg ha^{-1})	n.d.	n.d.	17.45	Tabatabai (1994)
Exchangeable Ca (meq 100 g^{-1})	n.d.	n.d.	8.14	EDTA titration
Exchangeable Mg (meq 100 g^{-1})	n.d.	n.d.	9.71	EDTA titration
Zn (mg kg^{-1})	n.d.	n.d.	1.58	Lindsay & Norvell (1978)
Cu (mg kg^{-1})	n.d.	n.d.	2.31	Lindsay & Norvell (1978)
Fe (mg kg^{-1})	n.d.	n.d.	167.51	Lindsay & Norvell (1978)
Mn (mg kg^{-1})	n.d.	n.d.	7.12	Lindsay & Norvell (1978)
H (%)	0.103	n.d.	n.d.	CHNS analyzer
S (%)	0.028	n.d.	n.d.	CHNS analyzer

n.d. – not determined

2.3 Soil Sampling and Analysis

Post-harvest soil samples (0-15 cm depth) were collected from the groundnut plots following a zig-zag pattern to form a composite sample per treatment. Samples were air-dried, ground, and passed through a 2-mm sieve for physicochemical analysis. A subset was stored at 4°C for microbiological and enzymatic assays, which were completed within 15 days of sampling.

Soil analyses were conducted using established standard methods. Texture was determined by the hydrometer method (Bouyoucos, 1962). Bulk density was measured using a core sampler (Blake and Hartge, 1986), while particle density and porosity were determined with a pycnometer (Flint and Flint, 2002). Water holding capacity was assessed using a Keen-Raczkowski box and penetration resistance with a cone penetrometer (Piper, 1950). Soil pH and electrical conductivity (EC) were measured potentiometrically and conductometrically, respectively (Jackson, 1973). Organic carbon (OC) was estimated by the rapid titration method of Walkley and Black (1934). Available nitrogen (N) was determined by the alkaline potassium permanganate method (Subbiah and Asija, 1956). Available phosphorus (P) was extracted with 0.5 M $NaHCO_3$ (pH 8.5) and measured spectrophotometrically (Olsen et al., 1954). Available potassium (K) was extracted with 1 N ammonium acetate (pH 7.0) and analyzed by flame photometry (Jackson, 1973). Exchangeable calcium (Ca) and magnesium (Mg) were determined by complexometric titration (Baruah and Barthakur, 1997). Available silicon (Si) was extracted with 0.01 M $CaCl_2$ and estimated spectrophotometrically (Haysom and Chapman, 1975). DTPA-extractable micronutrients (Zn, Fe, Cu, Mn) were quantified using atomic absorption spectrophotometry (Lindsay and Norvell, 1978). Urease activity was measured colorimetrically (Tabatabai, 1994). Acid and alkaline phosphatase activities were assessed by monitoring p-nitrophenol release from p-nitrophenyl phosphate (Tabatabai, 1994). β-glucosidase and arylsulfatase activities were determined by the methods of Tabatabai (1994). Dehydrogenase activity was estimated as described by Casida et al. (1964).

2.4 Statistical Analysis

Data were subjected to Analysis of Variance (ANOVA) appropriate for a randomized block design using R software (version 4.4.1). Treatment means were compared using Fisher's Least Significant Difference (LSD) test at a 5% level of significance ($p < 0.05$). Principal Component Analysis (PCA) was performed to visualize multivariate relationships among the treatments and measured parameters.

3. RESULTS AND DISCUSSION

3.1 Soil Physical Properties

Soil texture was consistently sandy across all treatments (81.3–84.7% sand, 8.2–10.7% silt, 5.6–10.4% clay). Fly ash (FA) application improved several physical properties, though not all changes were statistically significant. The lowest bulk density (1.38 Mg m^{-3}) and highest porosity (44.74%) were recorded in the FA40+T3 treatment. Surface penetration resistance (SPR) was most reduced in the FA20+T3 and Lime+T3 treatments, showing an 84% decrease compared to the control (Table 2).

3.2 Soil Chemical Properties

Soil pH remained slightly acidic (5.36–5.98) and electrical conductivity (EC) was low (0.19–0.25 dS m^{-1}), with no significant differences induced by FA treatments. In contrast, soil organic carbon (SOC) increased significantly with higher FA doses, rising by 114.3% and 160.7% in the FA20+T3 and FA40+T3 treatments, respectively, compared to the control (Table 3).

3.3 Primary Nutrients

Available nitrogen (N) showed an increasing trend, though not solely attributable to FA dosage. Available phosphorus (P) and potassium (K) increased significantly with FA application. The FA40+T3 treatment resulted in the highest available P (40.6% increase) and K (49.2% increase) over the control (Table 3).

3.4 Secondary Nutrients and Silicon

A significant, dose-dependent increase in available sulphur (S) was observed, with the FA40+T3 treatment achieving a 100.7% increase over the control. Exchangeable calcium (Ca) and magnesium (Mg) were highest in the Lime+T3 treatment, though FA40+T3 recorded comparable Mg levels. Plant-available silicon (Si) content was greatly enhanced by FA, with the highest level (46.98 mg kg^{-1}) found in the FA40+T3 treatment (Table 3).

Table 2. Effect of FA-amendment on soil physical properties

Treatment	Sand (%)	Silt (%)	Clay (%)	Bulk density ($Mg\ m^{-3}$)	Particle density ($Mg\ m^{-3}$)	Porosity (%)	Water holding capacity (%)	Soil penetration resistance (kPa)
T1: Absolute control	81.3±2.07 ^{a}	8.2±0.98 ^{b}	10.4±2.16 ^{a}	1.49±0.22 ^{a}	2.51±0.11 ^{a}	39.97±0.10 ^{a}	32.97±0.80 ^{a}	184.0±23.02 ^{a}
T2: Recommended NPK	83.4±1.68 ^{a}	8.3±0.43 ^{b}	8.3±2.06 ^{ab}	1.47±0.05 ^{a}	2.53±0.14 ^{a}	41.78±4.85 ^{a}	28.83±3.53 ^{b}	76.3±1.10 ^{c}
T3: FYM at 5t ha^{-1}+recommended NPK	81.6±2.31 ^{a}	10.7±0.72 ^{a}	7.6±2.19 ^{ab}	1.44±0.15 ^{a}	2.52±0.24 ^{a}	42.94±0.44 ^{a}	30.40±2.63 ^{ab}	77.0±2.41 ^{c}
T4: FA10 t ha^{-1}+T3	82.7±2.94 ^{a}	9.3±0.98 ^{ab}	7.9±1.98 ^{ab}	1.41±0.02 ^{a}	2.53±0.20 ^{a}	43.71±1.88 ^{a}	31.77±2.33 ^{ab}	101.3±7.74 ^{b}
T5: FA20 t ha^{-1}+T3	82.0±2.25 ^{a}	9.0±0.28 ^{b}	8.96±2.47 ^{a}	1.39±0.06 ^{a}	2.50±0.12 ^{a}	44.16±5.93 ^{a}	33.20±0.17 ^{a}	29.3±3.25 ^{d}
T6: FA 40 t ha^{-1}+T3	84.7±1.10 ^{a}	9.6±1.37 ^{ab}	5.6±1.98 ^{b}	1.38±0.05 ^{a}	2.49±0.11 ^{a}	44.74±3.67 ^{a}	33.38±0.23 ^{a}	6.3±0.12 ^{e}
T7: Lime 0.2LR+T3	82.6±1.74 ^{a}	8.2±0.46 ^{b}	9.1±1.71 ^{a}	1.41±0.02 ^{a}	2.49±0.16 ^{a}	43.43±1.88 ^{a}	30.33±1.40 ^{ab}	29.7±1.36 ^{d}
MSE	3.70	0.77	3.31	0.01	0.02	9.56	4.17	75.2
LSD ($p<0.05$)	NS	1.56	3.23	NS	NS	NS	3.63	15.42

Values - (Mean ± std.dev)
NS – Non Significant

Table 3. Effect of FA-amendment on chemical properties of soil

Treatment	pH	EC ($dS\ m^{-1}$)	OC ($g\ kg^{-1}$)	PASi ($mg\ kg^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)	Ca ($meq\ 100\ g^{-1}$)	Mg ($meq\ 100\ g^{-1}$)	S ($kg\ ha^{-1}$)	Zn ($mg\ kg^{-1}$)	Cu ($mg\ kg^{-1}$)	Fe ($mg\ kg^{-1}$)	Mn ($mg\ kg^{-1}$)
T1: Absolute control	5.36±0.83 ^{a}	0.19±0.013 ^{c}	0.28±0.01 ^{e}	25.58±3.83 ^{c}	197.69±17.89 ^{b}	9.86±0.22 ^{c}	63.41±3.41 ^{c}	16.67±1.85 ^{c}	16.67±2.35 ^{d}	12.55±1.45 ^{d}	0.99±0.03 ^{c}	8.56±0.98 ^{b}	66.54±3.57 ^{c}	4.61±0.68 ^{ab}
T2: Recommended NPK	5.57±0.09 ^{a}	0.22±0.006 ^{abc}	0.35±0.02 ^{d}	23.54±2.40 ^{c}	203.87±23.24 ^{b}	11.60±1.33 ^{bc}	78.46±12.10 ^{b}	16.67±1.41 ^{c}	20.00±2.35 ^{c}	17.04±1.72 ^{c}	1.29±0.13 ^{ab}	11.04±0.71 ^{ab}	152.05±19.11 ^{b}	5.45±0.45 ^{a}
T3: FYM at 5t ha^{-1}+recommended NPK	5.56±0.64 ^{a}	0.24±0.034 ^{a}	0.48±0.03 ^{c}	35.49±3.57 ^{b}	216.23±10.93 ^{b}	11.72±0.86 ^{abc}	79.46±6.11 ^{b}	20.00±2.07 ^{b}	23.33±2.35 ^{b}	17.24±1.70 ^{c}	1.15±0.13 ^{bc}	10.21±0.88 ^{ab}	158.85±1.05 ^{ab}	5.20±0.22 ^{ab}
T4: FA10 t ha^{-1}+T3	5.61±0.31 ^{a}	0.23±0.020 ^{ab}	0.51±0.01 ^{c}	42.05±0.28 ^{a}	253.29±4.52	12.44±1.81 ^{ab}	85.62±0.84 ^{ab}	16.67±2.42 ^{c}	23.33±2.35 ^{b}	20.35±2.65 ^{bc}	1.31±0.07 ^{ab}	9.25±0.76 ^{b}	143.07±8.61 ^{b}	5.13±0.81 ^{ab}
T5: FA20 t ha^{-1}+T3	5.70±0.07 ^{a}	0.25±0.020 ^{a}	0.60±0.04 ^{b}	45.28±0.08 ^{a}	265.65±21.79 ^{a}	13.63±2.15 ^{ab}	86.58±1.28 ^{ab}	22.33±2.55 ^{a}	24.00±2.35 ^{b}	22.99±2.85 ^{ab}	1.32±0.11 ^{ab}	9.65±1.21 ^{ab}	153.85±22.75 ^{b}	5.18±0.08 ^{ab}
T6: FA 40 t ha^{-1}+T3	5.89±0.06 ^{a}	0.24±0.020 ^{a}	0.73±0.04 ^{a}	46.98±6.88 ^{a}	278.01±25.13 ^{a}	13.87±0.52 ^{a}	94.64±2.62 ^{a}	20.00±0.32 ^{b}	26.67±2.35 ^{a}	25.19±0.77 ^{a}	1.36±0.06 ^{a}	9.95±1.40 ^{ab}	161.02±8.59 ^{a}	5.22±0.62 ^{ab}
T7: Lime 0.2LR+T3	5.98±0.20 ^{a}	0.20±0.001 ^{bc}	0.47±0.01 ^{c}	40.93±3.65 ^{b}	253.29±30.54 ^{a}	13.39±0.47 ^{a}	80.92±7.84 ^{b}	23.33±0.66 ^{a}	28.00±2.35 ^{a}	17.32±2.49 ^{c}	1.16±0.11 ^{bc}	10.01±0.62 ^{ab}	181.04±11.99 ^{a}	4.36±0.18 ^{b}
MSE	0.21	0.0004	0.0008	14.55	295.04	1.61	35.31	3.59	1.87	3.93	0.01	0.95	179.7	0.24
LSD ($p<0.05$)	NS	0.037	0.05	6.78	30.55	2.26	10.57	3.37	2.43	3.52	0.19	1.74	23.84	0.87

Values - (Mean ± std.dev)

Table 4. Effect of FA-amendment biological properties of soil

Treatment	Urease*	Acid phosphatase*	Alkaline phosphatase*	Aryl sulphatase*	β-glucosidase*	Dehydrogenase*
T1: Absolute control	44.2±5.50 ^{d}	185.8±17.08 ^{d}	12.2±0.13 ^{d}	27.9±1.61 ^{d}	8.5±0.684 ^{f}	0.5±0.06 ^{e}
T2: Recommended NPK	48.1±6.13 ^{cd}	187.1±21.11 ^{d}	15.5±1.53 ^{d}	42.0±2.29 ^{c}	10.2±0.001 ^{e}	3.6±0.26 ^{d}
T3: FYM at 5t ha^{-1}+recommended NPK	50.9±0.37 ^{bcd}	189.5±5.96 ^{d}	24.1±1.24 ^{c}	50.6±5.08 ^{b}	14.2±1.132 ^{d}	4.2±0.52 ^{d}
T4: FA10 t ha^{-1}+T3	59.5±6.59 ^{b}	229.5±25.01 ^{bc}	38.5±3.15 ^{b}	72.8±6.57 ^{a}	17.8±0.097 ^{c}	6.9±0.71 ^{c}
T5: FA20 t ha^{-1}+T3	69.3±8.27 ^{a}	256.3±1.10 ^{b}	52.8±3.92 ^{a}	74.5±1.36 ^{a}	19.5±1.924 ^{b}	13.7±0.43 ^{b}
T6: FA 40 t ha^{-1}+T3	77.1±8.13 ^{a}	293.4±6.55 ^{a}	57.1±4.60 ^{a}	76.4±3.42 ^{a}	27.3±0.118 ^{a}	16.4±1.71 ^{a}
T7: Lime 0.2LR+T3	55.9±1.21 ^{bc}	211.0±10.72 ^{cd}	29.2±3.55 ^{c}	73.1±1.62 ^{a}	16.8±0.043 ^{c}	5.9±0.25 ^{c}
MSE	27.76	257.2	8.76	13.62	0.87	0.55
LSD (p<0.05)	9.37	28.53	5.26	6.56	1.66	1.32

**Unit: Urease (µg NH_4^+ g soil^{-1} 5 hr^{-1}), Acid phosphatase (µg pNP g soil^{-1} hr^{-1}), Alkaline phosphatase (µg pNP g soil^{-1} hr^{-1}), Aryl sulphatase (µg pNP g soil^{-1} hr^{-1}), B-glucosidase (µg pNP g soil^{-1} hr^{-1}), Dehydrogenase (µg TPF g soil^{-1} day^{-1}) Values - (Mean±std.dev)*

Table 5. Effect of FA-amendment on Yield and yield attributes of groundnut

Treatment	Kernel yield (kg ha^{-1})	Pod yield (kg ha^{-1})	Haulm yield (kg ha^{-1})	Biomass yield (kg ha^{-1})	Shelling (%)
T1: Absolute control	424.1±58.45 ^{e}	641.7±8.50 ^{c}	3797.8±310.8 ^{b}	4439.5±462.1 ^{c}	66.1±9.95 ^{a}
T2: Recommended NPK	603.1±40.71 ^{d}	900.5±96.8 ^{b}	3976.4±576.7 ^{b}	4876.9±645.3 ^{bc}	67.0±8.85 ^{a}
T3: FYM at 5t ha^{-1}+recommended NPK	617.5±64.56 ^{cd}	917.1±138.3 ^{b}	4246.1±305.8 ^{b}	5163.2±57.24 ^{bc}	67.2±0.25 ^{a}
T4: FA10 t ha^{-1}+T3	729.1±78.92 ^{bc}	1080.2±67.1 ^{ab}	4363.7±116.0 ^{b}	5443.9±306.6 ^{b}	67.5±0.49 ^{a}
T5: FA20 t ha^{-1}+T3	769.3±77.52 ^{ab}	1113.4±169.2 ^{a}	5247.8±198.1 ^{a}	6361.2±397.9 ^{a}	69.1±8.15 ^{a}
T6: FA 40 t ha^{-1}+T3	872.3±96.16 ^{a}	1226.5±0.77 ^{a}	5938.1±752.0 ^{a}	7164.6±650.3 ^{a}	70.9±8.85 ^{a}
T7: Lime 0.2LR+T3	814.0±34.77 ^{ab}	1185.7±136.2 ^{a}	3987.2±109.2 ^{b}	5172.9±549.7 ^{bc}	68.6±7.18 ^{a}
MSE	4323	13092	171017	213981	
LSD (p<0.05)	116.96	203.55	735.68	822.92	NS

Values - (Mean±std.dev)
NS – Non Significant

3.5 Micronutrients

DTPA-extractable zinc (Zn) and iron (Fe) levels were highest in the FA40+T3 treatment. Copper (Cu) and manganese (Mn) concentrations were not significantly influenced by FA application, with the highest values observed in the NPK-only and NPK+FYM treatments (Table 3).

3.6 Soil Enzyme Activities

Soil enzyme activities were significantly enhanced by FA amendments. The highest activities of urease, acid phosphatase (ACP), alkaline phosphatase (ALP), arylsulfatase (ARS), dehydrogenase (DHA), and β-glucosidase (BGU) were consistently recorded in the FA40+T3 treatment, followed by FA20+T3 (Table 4).

3.7 Groundnut Yield and Yield Attributes

Kernel and pod yields were maximized in the FA40+T3 treatment (872.3 and 1226.5 kg ha^{-1}, respectively), which outperformed the Lime+T3 and lower FA-dose treatments. Haulm and biomass yields followed a similar trend, with the highest values in the FA40+T3 plot. Shelling percentage was also highest in the FA40+T3 treatment (Table 5).

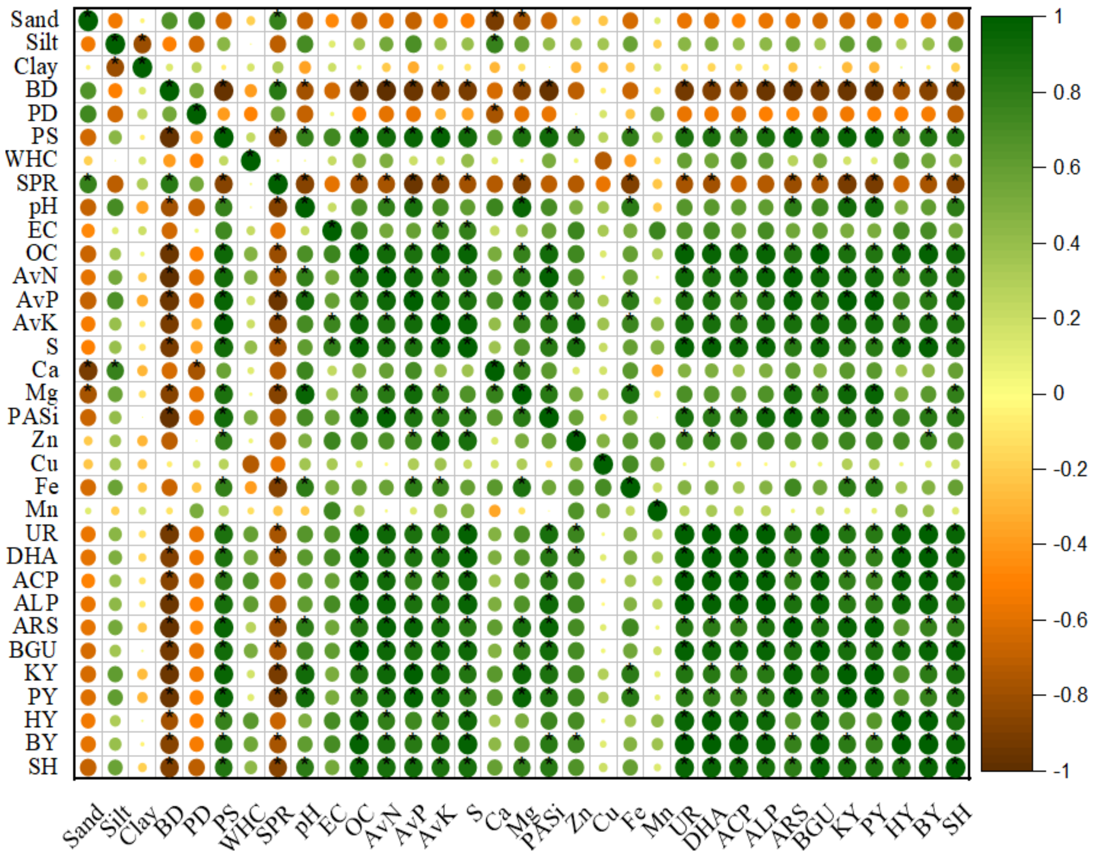

Fig. 1. Correlation matrix among soil parameters (*p≤0.05). The colour and size of each circle indicate the strength and direction of the correlation. Dark green and large circle represent strong positive correlation (closer to +1) while dark brown/orange and large represent strong negative correlation (closer to -1). Similarly, small or no circle represent weak or no correlation (close to 0). Abbreviation (BD: bulk density, PD: particle density, PS: Porosity, WHC: Water holding capacity, SPR: Soil penetration resistance, EC: Electrical conductivity, OC: Organic carbon, AvN: Available N, AvP: Available P, AvK: Available K, S: Available S, Ca: Exchangeable Ca, Mg: Exchangeable Mg, PASi, Plant available Si, Zn: DTPA extractable Zn, Cu: DTPA extractable Cu, Fe: DTPA extractable Fe, Mn: DTPA extractable Mn, UR: Urease, DHA: Dehydrogenase, ACP: Acid phosphatase, ALP: alkaline phosphatase, ARS: Arylsulphatase, BGU: β-Glucosidase, KY: Kernel yield, PY: Pod yield, HY: Haulm yield, BY: Biomass yield, SH: Shelling percentage)

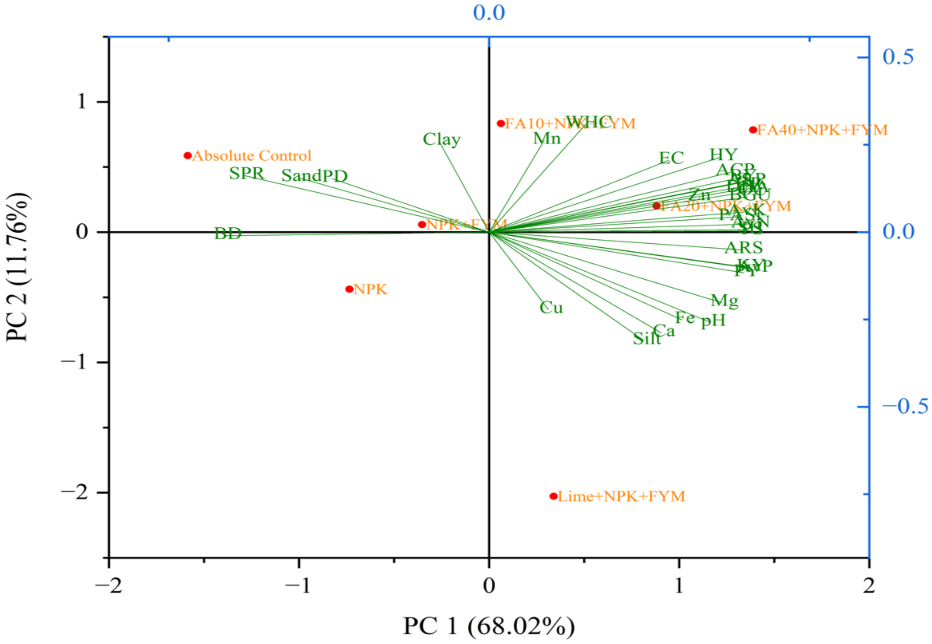

Fig. 2. Biplot of principle component analysis (PCA) showing the effect on soil properties and yield and yield attributes of groundnut due to different FA treatments.

3.8 Multivariate Analysis of Soil and Yield Parameters

Principal Component Analysis (PCA) and correlation analysis revealed strong relationships between soil properties, enzyme activities, and yield (Fig. 1, Fig. 2). PC1 (68.02% of variance) was strongly associated with soil fertility and yield attributes. Yield parameters (KY, PY), soil fertility indicators (OC, AvP, Ca, Mg, Fe), and enzyme activities (DHA, ALP, ARS) were positively correlated with each other and clustered together. Sand content, bulk density (BD), and soil penetration resistance (SPR) were negatively correlated with fertility and yield, indicating the detrimental effect of compaction. The PCA biplot clearly separated the absolute control and NPK-only treatments (associated with poorer soil properties) from the FA-amended treatments (FA40+T3, FA20+T3), which were strongly associated with improved soil fertility, microbial activity, and higher groundnut productivity.

4. DISCUSSION

4.1 Amendment-Induced Modifications to Soil Properties

The integration of fly ash (FA) with farmyard manure (FYM) presents a sustainable strategy for soil amelioration and waste management. Our findings demonstrate that FA application, particularly at higher doses (e.g., FA40+T3), positively influenced soil physical properties, consistent with previous studies (Ahmad et al., 2021). We observed reduced bulk density and soil penetration resistance, alongside increased porosity, suggesting improved soil structure and aeration conducive to root growth.

Notably, FA application did not significantly alter soil pH, likely due to the acidic nature of both the native soil and the FA used. This contrasts with studies utilizing more alkaline FA sources (Tejasvi & Kumar, 2012; Gond et al., 2013). We recorded a dose-dependent increase in soil organic carbon (OC) and major nutrients (N, P, K). The rise in available phosphorus may be attributed to reduced P fixation, a phenomenon also noted with other silicate amendments (Hong et al., 2018; Rautaray et al., 2003). Secondary nutrients (S, Ca, Mg) and plant-available silicon (PASi) were also enhanced, confirming FA's role as a nutrient source (Pandey & Singh, 2010; Lee et al., 2006). Among micronutrients, zinc showed the most pronounced response to FA addition.

Soil enzyme activities (urease, acid and alkaline phosphatase, dehydrogenase, β-glucosidase) were significantly enhanced, serving as robust biomarkers of improved microbial function and biochemical cycling (Nayak et al., 2014; Ramteke et al., 2017). This indicates that FA+FYM integration stimulates microbial processes vital for nitrogen mineralization (urease), phosphorus solubilization (phosphatases), and organic matter decomposition (dehydrogenase, β-glucosidase), thereby enhancing nutrient bioavailability.

4.2 Enhancement of Crop Productivity

Groundnut yield and yield attributes (kernel yield, pod yield, haulm yield, biomass, shelling percentage) exhibited a positive, dose-dependent response to FA application. The highest yields in the FA40+T3 treatment underscore the agronomic benefits of combined nutrient supplementation and soil physical improvement. The critical role of calcium in pod development was further highlighted by the strong performance of the lime-treated plots (Yang et al., 2020). These results align with previous work demonstrating the yield-enhancing potential of FA in groundnut cultivation (Swain et al., 2007; Sireesha & Rani, 2014; Nguyen et al., 2024).

4.3 Integrative Analysis of Soil-Plant Interactions

Multivariate analysis (correlation matrix, PCA) provided a synthesized understanding of treatment effects. The strong positive correlations between soil fertility indicators (OC, AvP, Ca, Mg), enzyme activities, and yield parameters confirm that FA amendments enhance productivity by improving the soil's physico-chemical-biological environment. Conversely, negative associations of yield with compaction indicators (BD, SPR) emphasize the importance of soil physical health.

The PCA clearly differentiated treatments, with high-dose FA amendments (FA40+T3, FA20+T3) clustering with improved soil properties and higher yields, while control treatments were associated with poorer soil conditions. This reinforces the conclusion that the integrated use of FA with organic and inorganic amendments is an effective strategy for enhancing soil quality and crop productivity within a sustainable framework.

5. CONCLUSION

This study demonstrates that fly ash, when applied in combination with farmyard manure and fertilizers, significantly improves soil physicochemical properties, nutrient availability, and microbial activity, leading to enhanced groundnut productivity in an acidic Inceptisol. The highest benefits were achieved with 40 t ha^{-1} FA, where improvements in organic carbon, available P, K, S, and Si were strongly associated with increased enzyme activities and yield gains. Multivariate analysis highlighted the integrative role of FA in modifying soil–plant interactions, with FA-amended treatments clustering with superior soil quality and crop performance. Importantly, the results establish FA as a viable soil amendment for recycling industrial waste into agricultural production systems. Future research should focus on long-term trials across diverse agroecological zones, with particular attention to heavy metal accumulation and crop-specific optimization, to develop safe, evidence-based recommendations. Harnessing FA for agriculture could transform an environmental liability into a sustainable resource for improving soil health, crop yields, and national food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

ACKNOWLEDGEMENTS

The first author sincerely acknowledges the Soil Science and Agricultural Chemistry Department of Odisha University of Agriculture and Technology (OUAT) for their invaluable support in soil sampling, laboratory analysis, and technical guidance. The financial assistance provided by the NTPC; New Delhi is gratefully acknowledged.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Ahmad, G., Khan, A. A., & 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.

Baruah, T.C. & Barthakur, H.P. 1997. A textbook on Soil Analysis. Vikas Publishing House PVT LTD, 576 Masjid Road, Jangpura, New Delhi 110 014.

Blake, G. R., & Hartge, K. H. (1986). Bulk density. *Methods of soil analysis: Part 1 Physical and mineralogical methods*, *5*, 363-375.

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*, *54*(5), 464-465.

Casida Jr, L. E., Klein, D. A., & Santoro, T. (1964). Soil dehydrogenase activity. *Soil science*, *98*(6), 371-376.

Down To Earth. (2019, July 12). *As told to Parliament (July 12, 2019): India doubled usage of fly ash in nine years*. https://www.downtoearth.org.in/mining/as-told-to-parliament-july-12-2019-india-doubled-usage-of-fly-ash-in-nine-years-65614

Flint, Alan L., & Lorraine E. Flint. "2.2 Particle Density." *Methods of soil analysis: Part 4 physical methods* 5 (2002): 229-240.

Ghosal, M. K., & Sarangi, P. (2020). Studies on Some Physical Properties of Groundnut of Devi (ICGV 91114) Variety. *Glob Acad J Agri Biosci*, *2*, 10-18.

Gond, D. P., Singh, S., Pal, A., & Tewary, B. K. (2013). Growth, yield and metal residues in Solanum melongena grown in fly ash amended soils. *Journal of Environmental Biology*, *34*(3), 539.

Haysom, M. B. C., & Chapman, L. S. (1975). Some aspects of the calcium silicate trials at Mackay. 117-122.

Hong, C., Su, Y., & Lu, S. (2018). Phosphorus availability changes in acidic soils amended with biochar, fly ash, and lime determined by diffusive gradients in thin films (DGT) technique. *Environmental Science and Pollution Research*, *25*(30), 30547-30556.

Jackson, M. L. (1973). *Soil chemical analysis-advanced course: A manual of methods useful for instruction and research in soil chemistry, physical chemistry of soils, soil fertility, and soil genesis*. author.

Jala, S., & Goyal, D. (2006). Fly ash as a soil ameliorant for improving crop production—a review. *Bioresource technology*, *97*(9), 1136-1147.

Kumar, A., Usmani, Z., & Kumar, V. (2017). Biochar and flyash inoculated with plant growth promoting rhizobacteria act as potential biofertilizer for luxuriant growth and yield of tomato plant. *Journal of environmental management*, *190*, 20-27.

Lal, K., Chhabra, R., Mongia, A. D., Meena, R. L., & Yadav, R. K. (2012). Release and uptake of potassium and sodium with fly ash application in rice on reclaimed alkali soil. *Journal of the Indian Society of Soil Science*, *60*(3), 181-186.

Lee, H., Ha, H. S., Lee, C. H., Lee, Y. B., & Kim, P. J. (2006). Fly ash effect on improving soil properties and rice productivity in Korean paddy soils. *Bioresource technology*, *97*(13), 1490-1497.

Lindsay, W. L., & Norvell, W. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil science society of America journal*, *42*(3), 421-428.

Nayak, A. K., Kumar, A., Raja, R., Rao, K. S., Mohanty, S., Shahid, M., ... & Bhattacharyya, P. (2014). Fly ash addition affects microbial biomass and carbon mineralization in agricultural soils. *Bulletin of environmental contamination and toxicology*, *92*, 160-164.

Nguyen, V. L., Chu, H. D., & Nguyen, D. H. (2024). Effects of fly ash application on the growth and disease resistance of peanut plants (Arachis hypogaea) cultivated in different soil types. *Vegetos*, 1-8

NTPC (2023). Ash Utilization. https://ntpc.co.in/about-us/corporate-functions/ash-utilisation

Olsen, S. R. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (No. 939). US Department of Agriculture.

Pandey, V. C., & Singh, N. (2010). Impact of fly ash incorporation in soil systems. *Agriculture, ecosystems & environment*, *136*(1-2), 16-27.

Piper, S. C. S. 1950. Soil and plant analysis. Univ. *Inter Sci. publishers. Inc. New york. Adelaide*, 258-275.

Ram, L. C., & Masto, R. E. (2014). Fly ash for soil amelioration: a review on the influence of ash blending with inorganic and organic amendments. *Earth-Science Reviews*, *128*, 52-74.

Ramteke, L. K., Sengar, S. S. & Porte, S. S., 2017, Effect of fly ash, organic manure and fertilizers on soil microbial activity in rice-wheat cropping system in Alfisols and Vertisols. Int. J. Curr. Microbiol. App,6(7): 1948-1952.

Rautaray, S. K., Ghosh, B. C., & Mittra, B. N. (2003). Effect of fly ash, organic wastes and chemical fertilizers on yield, nutrient uptake, heavy metal content and residual fertility in a rice–mustard cropping sequence under acid lateritic soils. *Bioresource Technology*, *90*(3), 275-283.

Singh, J. S., & Pandey, V. C. (2013). Fly ash application in nutrient poor agriculture soils: impact on methanotrophs population dynamics and paddy yields. *Ecotoxicology and Environmental Safety*, *89*, 43-51.

Sireesha, A., & Rani, P. P. (2014). Effect of flyash and fertilizers on yield, nutrient uptake and soil nutrient status of groundnut (Arachis hypogea).

Subbiah, B. V., & Asija, G. L. (1956). A rapid procedure for the estimation of available nitrogen in soils.

Swain, D. K., Rautaray, S. K., & Ghosh, B. C. (2007). Alkaline coal fly ash amendments are recommended for improving rice-peanut crops. *Acta Agriculturae Scandinavica Section B-Soil and Plant Science*, *57*(3), 201-211.

Tabatabai, M. A. (1994). Soil enzymes. *Methods of soil analysis: Part 2 Microbiological and biochemical properties*, *5*, 775-833.

Tejasvi, A., & Kumar, S. (2012). Impact of fly ash on soil properties. *National Academy Science Letters*, *35*, 13-16.

Walkley, A., & 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*(1), 29-38.

Woodruff, C. M. (1948). Testing soils for lime requirement by means of a buffered solution and the glass electrode. *Soil Science*, *66*(1), 53-64.

Yang, S., Wang, J., Tang, Z., Guo, F., Zhang, Y., Zhang, J., ... & Li, X. (2020). Transcriptome of peanut kernel and shell reveals the mechanism of calcium on peanut pod development. *Scientific reports*, *10*(1), 15723.

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/144311