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CHARACTERIZATION OF FLY ASH AND ITS POTENTIAL SOURCE IN AGRICULTURAL SOIL AMENDMENT AS AN INTEGRATED NUTRIENT SUPPLEMENT FOR RICE PLANT

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ABSTRACT

Fly ash, a byproduct of coal combustion in thermal power plants, holds promising potential as a sustainable soil amendment, especially in the agricultural sector. This study investigates the physico-chemical characterization of fly ash and evaluates its viability as an integrated nutrient supplement for rice (*Oryza sativa*) cultivation. A pot experiment was conducted with four treatment levels of fly ash 10 g, 20 g and 30 g per pot alongside a control group. Photosynthetic pigments including chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids, were measured at five Days Interval (7th, 14th, 21st, 28th, and 35th day) to assess their effect on rice growth. Physico-chemical parameters of soil such as pH, electrical conductivity, organic matter, nitrogen and phosphates were analyzed post treatment. Morphological and elemental analysis of fly ash was conducted using Scanning Electron Microscopy, X-Ray Fluorescence and X-Ray Diffraction, while toxicity levels were assessed using the Toxicity Characteristic Leaching Procedure. The results revealed that photosynthetic pigments, particularly chlorophyll a, chlorophyll b and carotenoids, peaked in the 20 g treatment. One way ANOVA showed statistically significant differences ($p < 0.05$) among the treatments. Soil tests indicated that parameters such as pH and nutrient content (except N, P and K) increased with higher fly ash doses. Correlation analysis demonstrated a negative relationship between pH and nitrogen content. XRF results confirmed that SiO_2, Al_2O_3 and Fe_2O_3 were the dominant components in the fly ash, with Zn showing the highest mobility in TCLP tests. XRD analysis further confirmed the crystalline nature of the fly ash constituents.

KEY WORDS: Fly ash, XRF, XRD, Amendment, Sustainable development

INTRODUCTION

Agriculture remains a cornerstone of global economies, providing essential resources such as food, raw materials and employment. It is integral not only to national development but also to poverty alleviation and the sustenance of livelihoods worldwide (Saeed *et al*., 2019; Cervantes and Dewbre, 2010; Raihan, 2023). To adequately nourish the current global population of 7.9 billion, an estimated 2.3 billion tons of cereals are required annually. Looking ahead, ensuring global food security will necessitate a 60% rise in agricultural output by 2050 (Ammarg *et al.*, 2003; Hou, 2023). This presents a formidable challenge, calling for sustainable and efficient agricultural practices to secure food availability for future generations (Sandstrom *et al.*, 2023). In response to growing demand, modern agriculture has increasingly relied on genetic modification, chemical fertilizers, plant growth regulators, pesticides, herbicides, and soil sterility to shorten crop cycles and maximize yields (Husain *et al*., 2023). However, the excessive and often unregulated use of these agrochemicals has led to several ecological concerns, including degradation of soil health, loss of soil organic matter, and disruption of agroecosystem functions. These challenges highlight the urgent need for sustainable and environmentally friendly alternatives to support long term agricultural productivity. The intensive use of chemical inputs in modern agriculture has increasingly threatened soil biodiversity, affecting both microbial and mesofaunal communities (Zhang *et al*., 2023; Derrien, *et al.,* 2023). To ensure a sustainable future, agricultural practices must not only meet the present demand for food and fiber but also preserve environmental integrity for generations to come (Bamdad *et al.,* 2022). Achieving this balance necessitates improved soil health and nutrient efficiency. However, the widespread reliance on synthetic fertilizers and chemical pesticides has degraded soil ecosystems and introduced harmful residues into food chains, potentially impacting human health (Panda and Dash, 2020; Chen and Li, 2006). In contrast, the integration of organic amendments and bio pesticides derived from natural sources offers a more ecofriendly alternative for enhancing soil fertility and pest control (Shukla *et al.,* 2019). Numerous studies have examined the efficacy of composts, organic manures, and alternative nutrient sources in reviving soil quality and boosting crop yields. The development of sustainable, environmentally sound fertilizers and bio pesticides remains a significant challenge for the current generation of scientists and farmers. Among the emerging options, coal based fly ash has garnered attention as a potentially sustainable mineral amendment with both nutrient supply and pest management capabilities (Vitekari *et al*., 2012; Varsgney *et al.,* 2022). Globally, around 53% of electricity is still derived from lignite coal, with India generating approximately 70% of its electricity through coal-fired thermal power plants (Arora and Gargava, 2023). As urbanization intensifies, the country's dependence on coal based electricity is projected to rise significantly, reaching about 40% of total energy use by 2030 (Das and Rout, 2023). These power plants produce large quantities of fly ash as a byproduct of coal combustion. Indian coal, known for its high ash content (30-60%), contributes heavily to the fly ash burden (Sun *et al*., 2016). Every year, substantial government resources are allocated to managing this waste stream (Quadir *et al.,* 2019). As of 2020, global fly ash generation ranged between 300 to 600 million tons annually, occupying nearly 3,235 square kilometers of land for disposal purposes (Hou *et al.,* 2023; Hu *et al*., 2021). During 2021–2022, India alone generated approximately 271 million tonnes of fly ash from about 200 thermal power stations. According to the coal ash report (2022) from the Ministry of Power, 259.86 MT of this total was reused, while the remaining stockpile continued to pose serious disposal concerns. It is estimated that unutilized fly ash requires over 2,300 hectares of land and around 1.3 billion cubic meters of water for ash pond storage (Mohan *et al*., 2012). The growing stockpile of fly ash necessitates its beneficial utilization rather than treating it as industrial waste. Increasing its application in environmentally beneficial avenues not only addresses disposal challenges but also yields economic benefits (Dwibedi and Pandey, 2023; Bhatt *et al*., 2019; Varshney *et al*., 2019; Oncioiu *et al.,* 2018). Improper disposal of fly ash can lead to severe environmental and human health issues due to the presence of heavy metals. Toxic elements such as arsenic, cadmium, chromium, lead, and mercury are known to cause adverse effects on vital organs including the liver, kidneys, nervous system, and digestive tract (Singh *et al*., 2011; Pandey *et al*., 2018). Moreover, these metals can elevate the alkalinity of nearby water bodies and degrade water quality (Khan and Umar, 2019). Uncontrolled leaching from fly ash dumps may release these hazardous elements into groundwater, while air dispersion of fly ash particles contributes to smog and respiratory issues (Yao *et al*., 2015; Roy *et al*., 2018; Smol *et al*., 2020). The calcium content in fly ash can also alter the pH of soils and water systems, further impacting ecological balance. To mitigate these risks and support sustainable development goals, it is imperative to maximize the utilization of fly ash through innovative agricultural applications (Rao *et al*., 2018). Fly ash is primarily composed of amorphous ferro-alumino silicate particles, structurally similar to soil, although it lacks significant amounts of phosphate, nitrogen, and organic carbon. Despite this, it is enriched with numerous essential plant nutrients, offering great potential to improve soil health, crop productivity, and even act as a bio control agent against pests. Although the Indian government supplies fly ash free of cost to farmers residing within a 300 kilometer radius of thermal plants, its use in agriculture remains limited (Ram and Masto, 2014). Research has shown that incorporating fly ash into loamy soils can enhance soil aggregation, alter porosity, and improve overall structure (Hussain and Faizan, 2023). It supplies vital macro, micro and trace elements such as phosphorus, potassium, calcium, magnesium, manganese, zinc, copper, boron, sulphates, carbonates, bicarbonates, and chlorides, which contribute to soil nutrient enrichment and plant development (Raleisena *et al*., 2023; Grabowska *et al*., 2021). The physicochemical and biological attributes of soils can be markedly improved with the application of fly ash. Fly ash amendments in the range of 10-40% by weight have been found to positively influence soil texture, water holding capacity, electrical conductivity, micro porosity, dry bulk density and pH. These changes also improve the permeability and infiltration properties of soils, with benefits observed in both clay rich and coarse textured soils ((Shakeei *et al*., 2019; Carlson and Adriano, 1993). Additionally, fly ash has been shown to enhance the cation exchange capacity, contributing to its function as a soil stabilizer, particularly in arid and semi arid regions prone to desertification (Ahmaruzzaman, 2010; Carlic *et al*., 2013). Recent years have seen extensive field experimentation to assess fly ash as a soil conditioner and low-cost fertilizer. Fly ash applications ranging from 100 to 650 tons per hectare have demonstrated improvements in plant biomass and productivity (Rao *et al*., 2020). Multiple independent studies have also confirmed yield enhancements in rice (*Oryza sativa* L.) when treated with fly ash, with reported increases of 2-8%, 40%, and even up to 90 Mg ha^{-1}, depending on experimental conditions (Ram and Masto, 2014; Grabowsha *et al*., 2021). Furthermore, fly ash application at 50% in upland soils led to improved growth performance and elevated antioxidant profiles in wild rice cultivars. Moreover, the nature and composition of fly ash itself fluctuates depending on the type and purity of coal used in power generation including peat, lignite, sub-bituminous, bituminous, anthracite, graphite, cannel coal, and coking coal (Yu *et al*., 2012). Therefore, unregulated or excessive application of fly ash without prior characterization of soil, water, and the fly ash material itself could pose serious environmental and agronomic risks. Despite its potential, fly ash usage in Indian agriculture remains marginal, accounting for merely 0.06% of total fly ash generation in 2021-2022. This underutilization may be attributed to the lack of awareness among farmers regarding the nutrient potential of fly ash, coupled with uncertainty surrounding its variable composition. To maximize the safe and effective use of fly ash in agriculture thorough assessment of its physicochemical and elemental properties is essential. Such evaluations will enable the formulation of tailored recommendations regarding appropriate fly ash application rates for specific crop soil water combinations. This study, emphasizes the urgent need for integrated characterization of soil, water and fly ash samples to assess compatibility and promote sustainable agricultural practices. Ultimately, this approach will contribute toward a farmer centric roadmap for the effective and environmentally sustainable use of fly ash in agriculture.

MATERIALS AND METHODS

Study area and sample collection

The present study was conducted in the ACC Cement of Bargarh district, Odisha, India. Fly ash samples were collected from a nearby industrial site, whereas agricultural soil samples were obtained from the experimental fields within the same region. The study area is illustrated in Figure 1. The soil samples were air dried, crushed gently, and passed through a 2 mm sieve to ensure uniformity before analysis. The fly ash sample, shown in Figure 2 was also sieved and stored in airtight containers for further evaluation. Both soil and fly ash samples

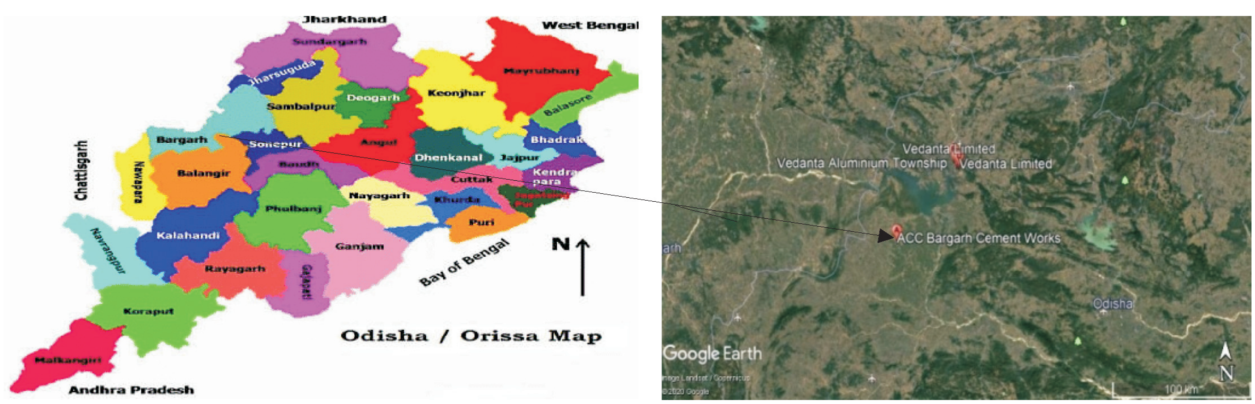

Fig. 1. Sampling area in Google map)

Fig. 2. Fly ash sample)

were subjected to physico-chemical characterization.

Physico-chemical analysis of soil samples

The pH was measured in a 1:5 (w/v) soil to distilled water suspension using a calibrated digital pH meter. Electrical conductivity was determined with a conductivity meter on similarly prepared suspension and expressed in mS/cm. Organic carbon and organic matter content were estimated by Wakley and Black (1934) method. Nitrate was quantified as per the procedure by Rrvels and Avnimlech (1979). Flame photometric analysis was employed to estimate sodium and potassium concentrations in the soil extract. Phosphate content was determined using ammonium molybdate colorimetry method.

Pot culture experimental design

To assess the impact of fly ash on rice plant growth, a pot experiment was conducted using plastic pots (50 cm × 50 cm × 60 cm) and 10 g, 20 g , 30 g of fly ash were applied in each pot with a control was taken. Each pot was filled with soil mixed uniformly with the respective fly ash concentration. Fifteen rice seeds were sown equidistantly per pot. Pots were irrigated regularly and maintained under natural sunlight conditions. The experiment was carried out for a period of 35 days, during which various plant growth and pigment parameters were monitored.

Estimation of photosynthetic pigments

Photosynthetic pigments such as chlorophyll a, chlorophyll b, total chlorophyll and carotenoids were quantified from fresh rice leaf using Aron (1949). One g of fresh leaf was homogenized in 80% acetone, centrifuged at 4000 rpm for 20 minutes and the absorbance of supernatant was measured at 475 nm, 645 nm, and 663 nm using a UV-Vis spectrophotometer. The pigment concentrations were calculated using the following formulae:

Chlorophyll-a (mg/g fresh tissue) = 12.7 × A663 - 2.69 × A645 × V / (1000 × W)

Chlorophyll-b (mg/g fresh tissue) = 22.9 × A645 - 4.68 × A663 × V / (1000 × W)

Carotenoids (mg/g fresh tissue) = A470 × V / (2500 × W)

Where,

A = Absorbance at specific wavelength, V = Final volume of the extract (mL), W = Fresh weight of leaf sample (g)

Measurement of morphological parameters

Morphological attributes such as root length, shoot length, and total plant height were recorded on the 7th day after germination. Observations were made by carefully uprooting the seedlings from each pot. Each treatment was replicated three times. The germination percentage (G%) was calculated based on visible radicle emergence (≥ 1 mm) using the formula:

Germination Percentage (G%) = (Number of seeds germinated / Total number of seeds sown) × 100

Morphological identification of fly ash through scanning electron microscopy (SEM)

The surface morphology and microstructure of the fly ash samples were analyzed using a scanning electron microscope (Hitachi S3400N). Samples were gold coated to improve conductivity prior to imaging. The SEM micrographs were captured at various magnifications to observe surface texture, particle size distribution, structural integrity with images recorded at a resolution of 50.0 ìm.

Leaching test

The collected sample was mixed with an acetic acid extraction fluid at a 20:1 liquid to solid ratio. The mixture is agitated for 18 hours on a rotary shaker to simulate leaching. After agitation, the sample is filtered using a 0.45 micron filter to separate the liquid from the solids. The leachate is analyzed for contaminants like heavy metals and organic compounds using techniques such as ICP-MS. Results are compared to regulatory limits to determine if the waste is hazardous.

RESULTS AND DISCUSSION

Elemental composition of fly ash by X-Ray fluorescence (XRF)

The X-ray fluorescence (XRF) analysis revealed a comprehensive profile of the elemental composition of fly ash, as summarized in Table 1. The dominant oxides present were SiO_2 (57.4%), Al_2O_3 (29.0%), and Fe_2O_3 (4.73%), together constituting 91.13% of the total oxide content. This high concentration indicates a typical class F fly ash, known for its pozzolanic properties and lower calcium content, which makes it suitable for agricultural soil amendments and geotechnical applications (Kumar and Singh, 2021; Pandey and Singh, 2010). The significant presence of SiO_2 and Al_2O_3 is beneficial for improving soil texture and enhancing nutrient retention capacity, whereas Fe_2O_3 can influence redox reactions in soil systems and promote plant growth under iron deficient conditions (Andriano *et al.*, 1980; Jala and Goyal, 2006). Moderate amounts of CaO (2.76%), TiO_2 (2.30%), and K_2O (1.54%) contribute to soil nutrient enrichment and can assist in balancing pH levels, especially in acidic soils (Bliskl, 2013). Trace elements such as MgO (0.591%), P_2O_5 (0.582%), SO_2 (0.524%), and others like MnO, ZnO, and CuO, though present in small quantities, play a crucial role as micronutrients for plant metabolism (Kalra *et al.*, 2003; Mishra and Shukla 1986). However, the presence of certain heavy metals such as PbO (0.011%), NiO (0.011%), and Cr_2O_3 (0%), although minimal or no detectable in this case, must be monitored to avoid potential toxicity to crops and water contamination upon long-term application (Carlson and Adriano, 1993). Overall, the elemental composition of the fly ash examined indicates a favourable potential for use as a soil amendment in sustainable agriculture. The high pozzolanic content suggests improved physical and chemical soil properties, making it a viable component in integrated waste management strategies and environmentally friendly agricultural practices (Singh and Siddique, 2013).

Table 1. Percentage of elements in oxide form

Metals composition of fly ash (%)	
Na_2O	0.123
MgO	0.591
Al_2O_3	29.0
SiO_2	57.4
P_2O_5	0.582
SO_3	0.524
Cl	0.093
K_2O	1.54
CaO	2.76
TiO_2	2.30
V_2O_5	0.045
Cr_2O_3	0
MnO	0.046
Fe_2O_3	4.73
NiO	0.011
CuO	0.014
ZnO	0.013
Ga_2O_3	0.006
Rb_2O	0.012
SrO	0.029
Y_2O_3	0.008
ZrO_2	0.060
Nb_2O_5	0.008
BaO	0.092
PbO	0.011
$SiO_2+Al_2O_3+Fe_2O_3$	91.13 %

Classification of fly ash

According to ASTM 618 report, the fly ash samples A (91.13%) is classified as class F-type. The F type may be due to the quantities of alumina, silica and ferrite ($Al_2O_3+Fe_2O_3+SiO_2$) were more than 70 % and percentage of calcium content was low given data from Table 1 (ASTM, 2021).

Morphological analysis of fly ash

Fig. 3 the spherical size of fly ash was seems to be heterogenic in nature with lot of dissimilarities among the particles. Based on the morphological test results, the fly ash sample was found to be irregular shape may be due its handling process. The resistivity of heavy metals leaching mainly depends on the particles having relatively high density and nonporous outer surface (Zhang *et al.*, 2010; Singh *et al.*, 2015).

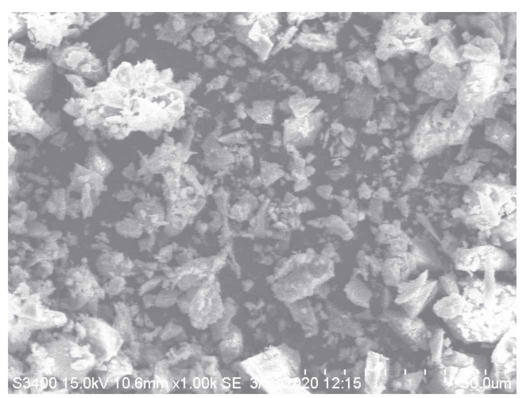

Fig. 3. Scanning electron microscope

Leaching test of fly ash sample

The leaching test of the fly ash sample was conducted to evaluate the potential environmental risk posed by heavy metals when applied to agricultural soils. The results, as presented in Table

2, indicate that most of the analyzed elements fall well below the permissible limits recommended by the World Health Organization (1996), indicating limited immediate environmental concern under standard agricultural conditions. Cadmium was detected at a very low concentration of 0.011 mg/kg, significantly below the WHO permissible limit of 0.8 mg/kg (Alloway, 2013). The low leach ability of cadmium from this sample indicates a negligible risk of soil or water contamination. Chromium and copper were found at 0.747 mg/kg and 1.296 mg/kg, respectively, both well below their respective WHO threshold values of 100 mg/kg for chromium and 36 mg/kg for copper. While chromium may exist in several oxidation states, Chromium is particularly toxic; however, fly ash typically contains chromium, which is less mobile (Singh and Kalmdhad, 2014). Similarly, copper is an essential micronutrient but toxic at high concentrations; its low leach ability suggests safe agronomic application (Adriano, 2001). Nickel, present at 0.416 mg/kg, remains under the critical threshold of 35 mg/kg, thus posing minimal ecological or phytotoxic threat. Excessive nickel can impair plant physiological functions, but its mobility in alkaline fly ash is typically restricted due to adsorption onto oxide surfaces (Gupta and Sharma, 2021). Lead was detected at 4.868 mg/kg, considerably lower than the WHO guideline value of 85 mg/kg. Although lead is not essential and toxic, especially to microbial communities and root systems, its mobility is often limited in alkaline and siliceous matrices like fly ash (Jala and Goyal, 2006). Thus, the potential for leaching into groundwater or accumulation in crops remains minimal. Zinc showed the highest concentration among all metals at 12.490 mg/kg, yet this is still within the permissible WHO limit of 140 mg/kg. Zinc is a vital micronutrient for plant growth; however, chronic exposure at high levels may be detrimental. The current level indicates possible agronomic benefits without exceeding toxic thresholds (Kabata and Touville, 2020; Hamidi *et al*., 2024). Other metals such as Manganese, Cobalt, Lithium and Strontium were detected in moderate concentrations (ranging from 0.063 to 3.300 mg/kg), for which WHO guidelines are not available. Their leach ability appears limited, but these elements may contribute to long term cumulative effects in soil systems depending on application rates and environmental conditions. Gallium was not detected in the sample, suggesting it is either absent or present below detection limits. Gallium is rarely found in significant concentrations in fly ash and generally poses low environmental risk (Fulekar, 2010). Overall, the results suggest that the tested fly ash possesses acceptable levels of leachable heavy metals and may be considered for beneficial reuse in agriculture, provided it is applied judiciously and site specific risk assessments are conducted. This aligns with previous studies advocating the use of fly ash as a soil conditioner due to its micronutrient content and ability to improve physical properties of degraded soils (Yadav *et al*., 2019).

Table 2. Concentration of heavy metals leached as a result of TCLP test mg/kg, ND- Not Detected

Sr. No.	Parameters	Sample (mg/Kg)	*Target Value of soil (mg/kg), WHO 1996
1	Cd	0.011	0.8
2	Co	0.063	-
3	Cr	0.747	100
4	Cu	1.296	36
5	Ga	ND	-
6	Li	0.717	-
7	Mn	3.300	-
8	Ni	0.416	35
9	Pb	4.868	85
10	Sr	1.688	-
11	Zn	12.490	140

*Target values are specified to indicate desirable maximum levels of elements in unpolluted soil)

X-Ray diffraction (XRD) analysis of fly ash

The X-ray diffraction (XRD) analysis of the fly ash sample (A1) was conducted to determine its mineralogical composition and crystalline structure. The resulting diffract gram is presented in Figure 4, showing diffraction peaks in the 2è range of 20° to 80°. The XRD pattern displays a dominant peak at

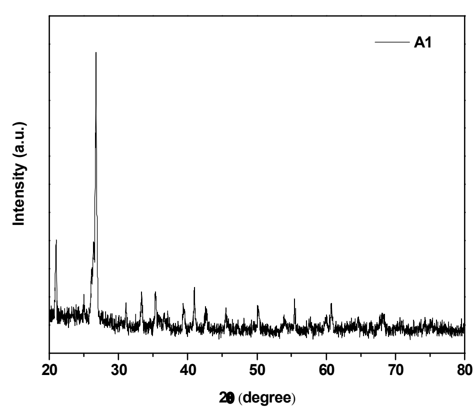

Fig. 4. XRD of fly ash sample

2θ ≈ 26.6°, which is attributed to the (101) plane of quartz (SiO_2), a ubiquitous mineral phase in fly ash derived from siliceous coal combustion. Quartz is known for its chemical inertness and contributes to the physical strength and particle stability in soil applications (Singh *et al.*, 2019). In addition to quartz, several smaller but distinguishable peaks were observed i.e mullite ($Al_2O_3·SiO_2$) peaks observed around 2θ ≈ 16.4°, 25.9°, and 40.8°. Mullite is a key alumino-silicate phase formed during high temperature combustion processes. It is chemically stable and contributes to the pozzolanic reactivity and mechanical strength of the material (Ramasamy *et al.,* 2021). Hematite (Fe_2O_3) a minor peak around 2θ ≈ 33.2° indicates the presence of iron oxides. These can influence redox reactions in soil and serve as micronutrient sources for plants. Magnetite (Fe_2O_3) and Anhydrite (CaSO) possibly observed at lower intensity peaks, indicating the presence of calcium and iron-bearing minerals which have implications for pH neutralization and nutrient availability in acidic soils (Jala and Oyal, 2006). The relatively sharp and well defined peaks across the diffractogram indicate a crystalline nature of the fly ash. However, the broad background hump, typically observed between 20° and 35°, suggests the presence of amorphous alumino-silicate glassy phases, which are highly reactive and enhance the pozzolanic behavior of fly ash (Gupta *et al.,* 2018). This mineralogical composition has direct implications for the use of fly ash in sustainable agriculture. Quartz and mullite enhance structural integrity, while amorphous phases contribute to nutrient retention and soil conditioning. The presence of iron and calcium compounds further promotes micronutrient enrichment and soil pH balance, making fly ash a promising candidate for soil amelioration and fertility enhancement from a practical, farmer oriented perspective.

In Table 3 the pH of fly ash sample was found to be alkali in nature i.e 7.89, the conductivity was 0.25 (µS/cm) of fly ash is a moderate level of soluble salts. The water holding capacity was 640 ml/ kg. The alkaline nature may be due to the presence of CaO, MgO in coal. The conductivity of this value was suggests that the fly ash can improve soil ion exchange capacity without significantly contributing to salinity issues. The high water holding capacity indicates that the fly ash has a porous microstructure capable of retaining substantial moisture (Ansari *et al.*, 2023).

Table 3. Fly ash physico-chemical parameters

Physico-chemical parameters of fly ash	
pH	7.89
Conductivity (ìS/cm)	0.25
Water holding capacity	640 ml/kg

The influence of varying concentrations of fly ash (0-30 g) on the physico-chemical properties of agricultural soil was investigated to assess its suitability as a soil amendment. The results, presented in Table 4, demonstrate significant changes in key soil parameters with increasing fly ash application, reflecting its dual role in nutrient enrichment and potential heavy metal contribution. Soil pH showed a gradual increase from 6.95 ± 0.898 (A_0) to 7.33 ± 0.049 (A_{30}) with increasing fly ash concentration. This alkaline shift can be attributed to the basic nature of fly ash, which typically contains oxides of calcium, magnesium, and other alkaline elements (Ram and Mohanty, 2022). An increase in electrical conductivity was also observed, rising from 50.0 ± 1.414 µS/cm to 91.8 ± 3.676 µS/cm, indicating higher salt content, which may impact seed germination and microbial activity at higher concentrations (Singh and Kalamdhad 2014). Organic carbon content slightly increased with fly ash amendment, from 7.2 ± 0.141% to 9.12 ± 0.070% at the highest dose. This may be due to the ash's surface adsorption capacity and improved microbial immobilization. Similarly, organic matter content increased from 12.41 ± 0.417% to 15.72 ± 0.933%, reflecting enhanced carbon sequestration potential (Adriano, 2001). A notable trend was the decrease in nitrate and phosphate levels with increasing fly ash addition. Nitrate declined from 7.0 ± 0.494 mg/kg (A_0) to 4.0 ± 1.141 mg/kg (A_{30}), and phosphate reduced from 9.8 ± 0.565 mg/kg to 2.6 ± 0.141 mg/kg. This decline may result from fly ash-induced pH changes that promote volatilization or reduce microbial nitrification and phosphate solubility (Yadav *et al.,* 2003). Conversely, sodium levels increased from 7.74 ± 0.212 mg/kg to 9.03 ± 0.685 mg/kg, and a slight decline in potassium content was observed, possibly due to ion exchange interactions or K fixation in ash amended soils. The WHC increased from 6.2 ± 0.424 ml/g to 7.2 ± 0.282 ml/g, indicating better soil structure and porosity due to the fine, porous nature of fly ash particles (Fulekar, 2010). Improved WHC is advantageous for plant water availability, especially in arid conditions. Calcium and aluminium concentrations increased with fly ash doses, reaching 7.93 ± 0.615 mg/g and 0.051 ± 0.003 mg/g respectively at A_{30}. Calcium

Table 4. Physico-chemical properties of agricultural soil samples in different concentration of fly ash application

Parameters	Concentration of fly ash amended in agricultural soil (gm)			
	A_0	A_{10}	A_{20}	A_{30}
pH	6.95±0.898	7.21±0.275	7.25±0.176	7.33±0.049
Conductivity (µs/cm)	50.0±1.414	75.2±2.969	86.3±1.442	91.8±3.676
OC (g%)	7.2±0.141	7.38±0.155	7.68±0.084	9.12±0.070
OM (g%)	12.41±0.417	12.72±0.367	13.24±0.254	15.72±0.933
Nitrate (mg/Kg)	7.0±0.494	6.8±0.282	5.2±0.0.565	4.0.±1.141
Phosphate (mg/Kg)	9.8±0.565	8.7±0.070	6.7±0.042	2.6±0.141
Sodium (mg/Kg)	7.74±0.212	9.0±0.707	9.02±0.141	9.03±0.685
Potassium (mg/Kg)	5.86±0.282	5.56±0.452	5.43±0.685	4.71±0.134
WHC (ml/g)	6.2±0.424	6.3±0.353	6.5±0.212	7.2±0.282
Ca (mg/g)	5.06±0.127	6.33±0.381	7.23±0.275	7.93±0.615
Al (mg/g)	0.039±0.002	0.042±0.004	0.048±0.005	0.051±0.003
Pb (mg/g)	0.175±0.003	0.196±0.002	0.201±0.003	0.205±0.007
Cd (mg/g)	0.005±0.001	0.007±0.002	0.008±0.001	0.010±0.002
Cr (mg/g)	0.147±0.005	0.162±0.004	0.175±0.028	0.186±0.613
Ni (mg/g)	0.225±0.002	0.215±0.002	0.213±0.001	0.212±0.005
Zn (mg/g)	0.205±0.002	0.174±0.001	0.168±0.004	0.162±0.002

enrichment improves soil buffering capacity, while aluminum increase should be monitored due to potential phytotoxicity at high concentrations (Saikia *et al.*, 2015).Trace metal concentrations such as Pb, Cd, Cr, Ni, and Zn slightly increased with increasing ash application. For example, lead increased from 0.175 ± 0.003 mg/g (A_0) to 0.205 ± 0.007 mg/g (A_{30}) and Cd from 0.005 ± 0.001 to 0.010 ± 0.002 mg/g. Though within acceptable limits, their cumulative presence necessitates careful monitoring to avoid long term soil contamination and uptake by crops (Jala and Goyal, 2006). Interestingly, zinc levels decreased slightly from 0.205 ± 0.002 mg/g (A_0) to 0.162 ± 0.002 mg/g (A_{30}) possibly due to sorption onto ash particles.

The bar graph (Figure 5) represents the percentage values recorded for control, A_{10}, A_{20}, and A_{30} treatments. The control sample exhibited the lowest value at 12%, establishing the baseline for comparison. Treatments A_{10}, A_{20}, and A_{30} all demonstrated higher percentages registering 30%, 35%, and 23%, respectively. Among the treatments, A_{20} achieved the highest value (35%), indicating the most significant improvement over the control, while A_{30} showed the least increase (23%) among the treated samples. The improved germination in the A_{10} treatment can be attributed to the enhancement of certain soil properties, such as increased organic matter, pH, and water holding capacity, which together fostered a more favourable seedbed environment. Previous studies have shown that low concentrations of fly ash can enhance soil aeration

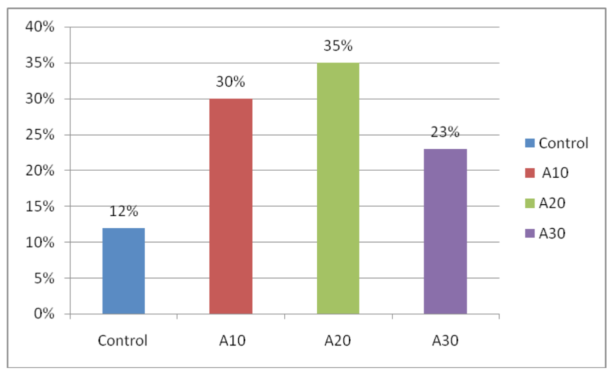

Fig. 5. Comparison between percentages of germination in different fly ash concentration

and nutrient availability, thereby stimulating seed metabolic activity and radical emergence (Chugh and Sarin, 2020; Gupta *et al.*, 2002). However, a decline in germination at the A_{30} level suggests phytotoxic effects due to excessive accumulation of heavy metals (Pb, Cd, Cr, Ni), increased salinity and reduced phosphate and nitrate availability. High concentrations of heavy metals and salts can impair enzymatic activity, disrupt cell membranes, and inhibit water uptake in seeds, ultimately affecting germination and early seedling growth (Kakar *et al.*, 2019; Pandey and Singh, 2010). This observation aligns with the findings of (Pandey and Singh, 2010), who reported an inhibitory effect on seed germination and seedling vigour at high fly ash concentrations, primarily due to osmotic stress and metal toxicity.

Figure 6 illustrates the increment percentages relative to the control treatment. The calculated increments were, A_{10} (150%), A_{20} (191.67%) and A_{30} (91.67%). These results reinforce the observations from the graph that, A_{20} exhibited the highest relative improvement, with a nearly threefold increase compared to the Control. This strongly indicates that the conditions or compositions associated with A_{20} were the most effective among those tested. A_{10} also performed well, showing a 150% enhancement, while A_{30} demonstrated a moderate improvement of about 91.67%. These findings suggest a dose dependent or composition dependent relationship between the treatment applied and the measured parameter. However, the slight reduction in effectiveness observed with A_{30} compared to A_{10} and A_{20} may imply that beyond a certain threshold, further treatment either plateaus in benefit or potentially induces diminishing returns.

The present study investigated the impact of different concentrations of fly ash (10 g, 20 g, and 30 g) on the selected parameter e.g., plant growth over a period of 35 days. The results, as shown in the

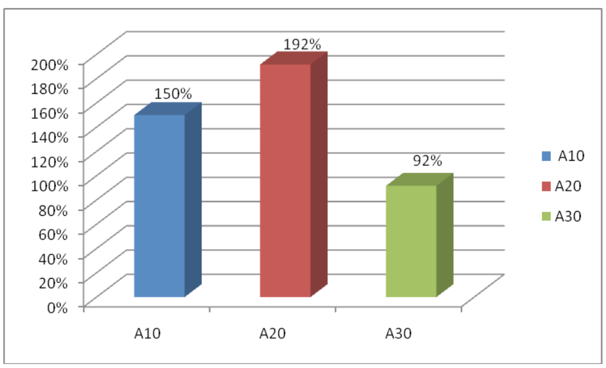

Fig. 6. Increment percentage over control

Table 5. Growth rate of rice plant in pot culture)Different concentrations of fly ash in g

Days	Control	10(g)	20(g)	30(g)
7 days	0.2	0.5	0.7	0.4
14 days	1.5	4	6	5
21days	3.5	9	14.2	12.5
28 days	10.5	16	19	16.4
35 days	15.5	18.5	19.7	16.5

Table 5, demonstrate a consistent trend of enhanced performance with increasing fly ash concentration up to a certain threshold. At 7 days, minimal growth was observed across all treatments, with the control recording the lowest value (0.2) and 20 g fly ash treatment slightly outperforming others at 0.7. This indicates that the initial period likely involved germination and early establishment, where the influence of fly ash was not yet fully pronounced. In14 days, a more noticeable effect emerged, with the 20 g treatment showing a marked increase (6.0) compared to control (1.5). The growth enhancement is likely due to the gradual availability of essential nutrients like calcium, magnesium, and trace elements present in fly ash (Adriano *et al*., 1989), which begin influencing soil fertility and microbial activity around this stage. At 21 and 28 days, the trend became more prominent. The 20 g fly ash application consistently showed superior growth (14.2 and 19.0) respectively, compared to both the control (3.5 and 10.5) and other treatments. This supports findings by Adrianno *et al*., (1980), who reported that moderate fly ash incorporation significantly improves soil structure and water retention capacity, resulting in better root development and nutrient uptake. By 35 days, the 20 g treatment retained the highest value (19.7) followed by 10 g (18.5) and 30 g (16.5). This suggests that while higher fly ash levels (30 g) initially promote growth, prolonged exposure may slightly inhibit performance, potentially due to excessive accumulation of trace metals or changes in pH levels (Sarkar *et al*., 2022). Thus, 20 g appears to be the optimum dose for enhancing the targeted growth parameter without invoking adverse effects. The gradual and sustained increase in values for 10 g and 20 g treatments aligns with prior research indicating that fly ash, when applied in moderate amounts, acts as an effective soil amendment. It enhances soil porosity, nutrient content, and water holding capacity, which is crucial for sustainable agriculture (Aditya *et al*., 2015). However, excessive application (30 g) may lead to accumulation of heavy metals such as arsenic and lead, which negatively affect plant growth and soil microbial dynamics over time. One way Analysis of Variance between different fly ash amended soil concentrations as well as within different days of growth rate of rice plant showed a significant difference ($F=7.513$; $p < 0.05$) (Table 5) (Basu *et al*., 2009).

Correlation analysis

Table 6 presents the correlation matrix for various physicochemical parameters of fly ash amended soil, revealing important interactions and dependencies among the soil, nutrient, and heavy metal characteristics. The correlation coefficients provide insights into the strength and direction of relationships between variables, ranging from -1 to +1, where values closer to ±1 indicate stronger correlations. One of the most notable findings is the strong positive correlation between pH and potassium (r = 0.99), suggesting that higher pH levels in the amended soil significantly promote potassium availability. This could be attributed to the alkaline nature of fly ash, which improves nutrient retention, particularly of base cations like Kz. Additionally, pH showed high correlation with sodium (r = 0.95) and phosphate (r = 0.81), indicating improved availability of these nutrients in alkaline conditions. Electrical conductivity also displayed strong positive correlations with several parameters such as nitrate (r = 0.84), potassium (r = 0.98) and sodium (r = 0.93), which may reflect enhanced ionic strength due to increased soluble salts in the fly ash treated soils. High EC may also be indicative of greater nutrient leaching or mobility under certain conditions, which warrants further agronomic consideration. Organic matter and organic carbon content showed a perfect correlation (r = 0.99), which is expected due to their interrelated nature. Both OM% and OC% were also positively correlated with nitrate (r = 0.92), phosphate (r = 0.97) and potassium (r = 0.77) suggesting that organic content supports nutrient retention and cycling. The water holding capacity demonstrated moderately strong correlations with organic matter (r = 0.98), phosphate (r = 0.99) and calcium (r = 0.85), implying that fly ash application could improve soil moisture retention through increased organic matter and cation availability. Regarding heavy metals, lead (Pb), cadmium (Cd), chromium (Cr) and zinc (Zn) generally showed strong positive correlations with most nutrient parameters and each other. For instance, Cd showed high correlations with potassium (r = 0.98), phosphate (r = 0.81), and Pb (r = 0.99), while Zn strongly correlated with phosphate (r = 0.95) and potassium (r = 0.99). These relationships highlight a potential risk of mobilization of heavy metals with nutrients, particularly under conditions favoring metal solubility (e.g., lower pH or higher EC).The results indicate that fly ash application significantly influences the physicochemical behaviour of soils, enhancing the availability of essential plant nutrients while also potentially increasing the mobility of heavy metals. This dual effect necessitates a balanced application strategy to maximize agricultural benefits while minimizing

Table 6. Correlation between the physico-chemical parameters of fly ash amendment soil

	pH	Conductivity	OC %	OM%	Nitrate	Phosphate	Sodium	Potassium	WHC	Ca	Al	Pb	Cd	Cr	Ni	Zn
pH	1															
Conductivity	0.98	1														
OC (%)	0.72	0.73	1													
OM (%)	0.72	0.73	0.99	1												
Nitrate	-0.79	-0.84	-0.92	-0.92	1											
Phosphate	-0.81	-0.83	-0.98	-0.98	0.97	1										
Sodium	0.95	0.93	0.50	0.50	-0.60	-0.61	1									
Potassium	0.99	0.98	0.77	0.77	-0.83	-0.85	0.93	1								
WHC	0.75	0.75	0.99	0.99	-0.94	-0.99	0.53	0.79	1							
Ca	0.96	0.98	0.83	0.83	-0.92	-0.91	0.85	0.97	0.85	1						
Al	0.88	0.93	0.86	0.86	-0.97	-0.94	0.74	0.90	0.89	0.97	1					
Pb	0.99	0.99	0.69	0.69	-0.78	-0.78	0.96	0.99	0.71	0.96	0.88	1				
Cd	0.94	0.95	0.90	0.90	-0.93	-0.95	0.81	0.96	0.92	0.98	0.96	0.92	1			
Cr	0.94	0.96	0.86	0.86	-0.94	-0.93	0.82	0.96	0.88	0.99	0.98	0.94	0.98	1		
Ni	-0.99	-0.98	-0.63	-0.63	0.74	0.74	-0.98	-0.97	-0.66	-0.93	-0.85	-0.99	-0.89	-0.91	1	
Zn	-0.99	-0.99	-0.68	-0.68	0.77	0.78	-0.97	-0.99	-0.70	-0.95	-0.87	-0.99	-0.92	-0.93	0.99	1

environmental risks (Rai *et al*., 2004; Pandey and Singh, 2010; Tripathi *et al.*, 2019).

CONCLUSION

The present study comprehensively investigated the characterization of fly ash and its potential as a sustainable soil amendment for rice cultivation integrating physicochemical analysis soil and controlled pot culture experiments. The results demonstrate that fly ash exhibits multifaceted benefits when utilized as a soil additive, contributing positively to soil fertility, nutrient dynamics and plant growth. The leaching tests of fly ash sample revealed that concentrations of heavy metals such as cadmium (0.01 mg/kg), chromium (0.74 mg/kg), copper (1.29 mg/kg), nickel (0.41 mg/kg), lead (4.86 mg/kg) and zinc (12.49 mg/kg) were all within the WHO recommended permissible limits for agricultural soils. Notably, cadmium, chromium and lead, although within safe thresholds, still require monitoring due to their potential ecological and biological risks under specific environmental conditions. Parameters such as cobalt, lithium, manganese, strontium and gallium (not detected) were also quantified, further affirming the fly ash's chemical suitability for controlled agricultural application. Experimental treatments compared to the control condition (12%) revealed substantial improvements. Treatments A_{10}, A_{20}, and A_{30} showed increased values of 30%, 35%, and 23%, respectively. Increment analysis indicated a 150% increase for A_{10}, a 191.67% increase for A_{20} (the highest), and a 91.67% increase for A_{30} compared to the control, highlighting the significant positive impact of fly ash amendments on the measured agricultural parameters. Fly ash treatments improved key soil attributes, including pH, water holding capacity and essential macro and micronutrient levels. Statistical correlations further validated these improvements: strong positive relationships between pH, electrical conductivity, organic carbon, nitrate, phosphate and water holding capacity (r = 0.99), and between organic matter and soil health (r = 0.99), demonstrate the synergistic effects of fly ash amendments on soil nutrient retention and organic matter dynamics. The application of 20 g of fly ash notably enhanced photosynthetic pigment concentration and rice plant growth, confirming its role as a viable integrated nutrient supplement. Nevertheless, while beneficial, the trace presence of heavy metals necessitates cautious management to mitigate potential mobilization risks under variable field conditions. In conclusion, fly ash, when strategically and carefully applied, holds substantial promise as a sustainable, cost effective and environmentally friendly alternative to conventional synthetic fertilizers. Its application not only improves soil fertility and plant productivity but also contributes to sustainable agricultural practices. However, long term field trials, dosage optimization studies, and adherence to regulatory frameworks are essential to fully harness the benefits of fly ash while minimizing associated environmental risks. Continued monitoring of heavy metal behaviour and soil plant interactions is strongly recommended to ensure ecological safety and sustainable soil management.

Conflict of Interest – None

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