ISSN Print: 2664-6064
ISSN Online: 2664-6072
NAAS Rating (2026): 4.69
IJAN 2026; 8(3): 04-08
www.agriculturejournal.net
Received: 03-12-2025
Accepted: 05-02-2026

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A systematic review of the effects of fly ash on soil properties, crop productivity and environmental risks in agriculture

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DOI: https://www.doi.org/10.33545/26646064.2026.v8.i3a.350

Abstract
Coal-fired thermal power plants remain the primary source of electricity generation in many areas of the developing world, with the resulting fly ash (FA) being one of the largest components of solid waste generated by these plants. Fly ash contains high levels of heavy metals and occasionally contains radioactive elements, making it difficult to dispose of safely and posing questions about environmental pollution, bioaccumulation, and human health risk. This study will examine the risks and potential agronomic benefits of fly ash in order to provide information that can help promote an appropriate balance between environmental safety and the potential for sustainable agricultural applications.

Keywords: Fly ash, thermal power plant, bioaccumulation, environmental pollution, human health risk

Introduction

Worldwide, coal is widely utilized as the main energy source for the production of electricity. FA is created as a byproduct of burning coal to generate energy in the thermal power plant (Basu *et al*., 2009; Patil *et al*., Kuznia, 2025) [6, 35]. More than 70% of India's electricity is produced by thermal power plants, which also produce significant amounts of FA. According to national figures for 2022-2023, only over 60% of the 140 million tons of FA generated were used successfully (Central Electricity Authority, 2023) [10].

From a circular economy standpoint, it is possible to utilize coal fly ash as a raw material for later use. Despite its potential to improve soil structure and increase soil organic matter, the mining of coal fly ash has been documented to cause several environmental harms. For instance, it has been demonstrated that an excess of coal fly ash decreases the soil's capacity to hold onto water and retain nutrients (Tripathi *et al*., 2020) [14]. By-products of the thermal energy production, such as fly ash (20%) and bottom ash (80%), are unavoidably produced and contain heavy metals, chlorides, and organic compounds (Chen *et al*. 2017, Dontriros *et al*. 2020) [13, 16]. Since bottom ash is believed to be less hazardous and difficult to work with than fly ash, it can be utilized as a construction material. The emission of fly ash with heavy metals is immediately concerning since it might create major health problems (Atanes *et al*. 2019) [4]. Fly ash is finely divided debris that is created when coal burns and is transported by the fuel gases of boilers that run on pulverized coal, claim Murugan and Vijayarangam (2013) [30]. Its present disposal method, which necessitated the use of vast areas of land as disposal sites, led to a number of environmental problems, including deteriorating groundwater quality, decreased soil productivity, impacts on the health of people and animals, and disruptions to the proper growth of higher plants (Tiwari *et al*. 2019) [46]. Fly ash stays above ground when transported by the wind or by vehicles to the disposal site because its particle sizes vary from 0.01 to 100 micrometers (Bhatt *et al*. 2019) [7].

Previously seen as a waste, coal fly ash is now attracting the attention of experts worldwide. The most troublesome issue of the century was how to dispose of it. Environmentalists and scientists are looking at every avenue to lessen the burden of coal fly ash, a waste byproduct produced during coal burning. Coal fly ash makes up 70-75% of all coal combustion byproducts on Earth; hence efforts were made to find every potential application for this residue. Fly ash is recommended for use in road building, as a liming material, and in conjunction with cement; nevertheless, during morphological examination and property investigation, it was shown to have a vast ability to alter the physical characteristics of soil. With its distinct structure, coal fly ash has been discovered to include a variety of macro and micronutrients that can alter the texture and other physical characteristics of soil over time. Fly ash may be utilized in agriculture as a natural manure source that can improve the development characteristics of plants because it also includes vital nutrients in its composition (Raj and Mohan., 2016) [38]. Rhizobium sp. populations benefited from the use of fly ash as a soil amendment, and the establishment of a number of soil-borne micropathogens was shown to be inhibited (Chandrakar *et al*., 2015) [12]. According to recent studies, coal fly ash can improve soil quality, enrich nutrients, and reduce deficiencies in the soil. Carbonated, sulphates, bicarbonates, K, P, B, Ca, Mg, Zn, and carbonated are all increased when coal fly ash is added (Yunusa *et al*. 2006) [49]. Fly ash is a possible fertilizer since it gives crops essential nutrients and minerals (Tiwari *et al*. 2016) [47]. The chemical composition, pH, and electrical conductivity of soil can all be altered by fly ash (Tejasvi 2017) [44]. This review looks at fly ash's potential for agriculture, related hazards, and sustainable management techniques.

2. Properties of fly ash

Fly ash's physico-chemical characteristics are influenced by the composition of the source coal, the furnace's combustion conditions, the ash's age, particle size, and collector configuration (Basu *et al*., 2009) [6]. Typically, fly ash is a silty loam with particles less than 0.01 mm in diameter. One of the key physical characteristics for qualitatively assessing the lime concentration is its color. Higher levels of organic matter are suggested by darker colors, whereas higher levels of calcium oxide are indicated by lighter colors. Coal ashes have a specific gravity of about 2.0, however it can range widely from 1.6 to 3.1 (McLaren and Digioia, 1987) [27]. Fly ash (FA) has a high surface area and a light texture because of its porous particles and other carbonaceous materials. FA particles can be large or small and spherical (Natusch & Wallace, 1974) [31], resulting in a variety of fly ash types with a wide range of characteristics, including specific weight (2.1-2.6 g cm-1), bulk density (1-1.8 g cm-1), moisture retention (6.1%-13.4%), and water retention (49%-66%) (Abhishek *et al*., 2025; Chakraborty *et al*., 2025) [1, 11].

The type of coal burned and the combustion process have a significant impact on the chemical composition of FA. The main constituents are usually silicon dioxide (20-60%), aluminum oxide (5-35%), and iron oxide (4-40%), with varying amounts of calcium oxide (1-40%) and minor oxides like magnesium, potassium, and sodium (usually less than 10%). In accordance with the mineral phases available and their buffering ability, FA can form leachates with pH values ranging from acidic to highly alkaline (about 4-12) when it comes into contact with water.

The composition and characteristics of fly ash are identical to those of coal. FA contains every element found in soil, with the exception of carbon and nitrogen (Kumar *et al*., 2000) [25]. Higher aluminum concentration is known to be organically hazardous, whereas FA contains aluminum in the form of an aluminosilicate structure, which is far less toxic (Page *et al*., 1979) [32]. Coal ash contains elements including Zn, Mn, Cu, Mo, and Se, as well as phosphorus (P) and boron (B), which are among the nutrients that many plants require.

3. Role of fly ash in soil management

3.1 Effect of fly ash on soil physico chemical properties

The influence of FA on soil has already been the subject of several studies. Because of the tiny particle size, alkalinity, and mineral makeup of the ash, applying FA to soil can cause substantial changes in its physical and chemical environment. The pH of the soil is one of the most noticeable consequences.

Following an alkaline fly ash treatment, it was demonstrated that the rapid release of Na, Ca, Al, and OH ions from fly ash raised the pH of the soil (Alterary and Marei 2021) [3]. According to Misra *et al*. (1991) [28], fly ash may be used as a liming material to balance the acidity of the soil and supply nutrients that plants can use. It has been demonstrated by researchers that applying fly ash as a liming agent to acidic soils may enhance soil characteristics and boost crop productivity (Mishra and Behera 1991) [29]. When fly ash is applied, the soil's electrical conductivity and metal concentration both rise.

According to reports, permeability and ability to hold water were increased by gradually increasing the fly-ash content in regular field soil (0, 10, 20, up to 100% v/v) (Kumar, A *et al*. 2003) [24]. Plant growth benefits from this increase in water-holding capacity, particularly in rain-fed agriculture. Fly ash amendments up to 40% also improved soil ability to retain water from 39 to 55% and the porosity of soil from 43 to 53% (Sippola *et al*. 2003) [42].

The incorporation of untreated FA to sandy soils significantly reduced microbial respiration, numbers, size, and enzyme activity as well as soil nitrogen cycle activities including nitrification and N mineralization, according to a number of short-term laboratory incubation experiments. There is relatively little information available about how fly ash amendments affect the biological characteristics of soil (Furlani *et al*. 2011) [17]. The high concentrations of trace elements and soluble salts in the unweathered fly ash contributed to these negative consequences. But when fly ash weathered during natural leaching, it was discovered that the quantity of water-soluble salts and other trace elements decreased, lessening the negative effects over time. The physico-chemical characteristics of fly ash surrounding the Badarpur thermal power plant were reported by Qadir and Siddiqui (2014) [36]. They discovered that the polluted locations had greater levels of silt, sand, pH, electrical conductivity, and metal concentration than the uncontaminated sites. When soluble salts boost electrical conductivity to suppressive levels or when large application rates raise pH over the ideal range for native microbial communities, microbial activity in FA-amended soils frequently exhibits an initial drop. However, with better nutrient availability (*e.g.*, Mo, P, B, and Ca) and improved moisture conditions, microbial biomass and activity of enzymes may recover or even exceed baseline levels when the soil-ash system equilibrates.

3.2 Effect of fly ash on crop production

Thick layers of fly ash limit the movement of water and reduce the amount of total light that is available to support photosynthesis and ultimately to reduce photosynthesis at all. Due to the ability of fly-ash-weighted leaves to retain heat better than leaves that do not contain fly ash, the temperature of such leaves increases, thus allowing them to transpire faster than normal leaves. Different plant species' shoots were carrying out distinct tasks that were impacted by fly ash particles above ground. Changes to soil characteristics as a result of the introduction of fly ash can have an immediate or mediated impact on microbial activity and root growth (Parab *et al*., 2015) [34].

The presence of large amounts of calcium, phosphorus, magnesium, potassium and sulphur in fly ash will result in the enhancement of nutrient uptake by the soil and thus increase the growth of plants (Kalra *et al*., 1997) [20], which would subsequently boost crop yields (Basu *et al*., 2007) [5]. The influence of an application rate of fly ash at 100 t ha-1 on the uptake of macronutrients by crops such as wheat, maize and eggplant when grown in rotation was evaluated by Tripathi *et al*. (2009) [48]. Greater levels of macronutrient uptake (K, S, N, Ca, P and Mg) from plants to the soil occurred after the application of fly ash. Additionally, they demonstrated that the application of fly ash improved the soil pool of micronutrients that plants might use, such as Mn, Zn, Fe, and Ni, while also modestly increasing the soil pool of certain harmful elements, such as Pb, Cr, Cu, Se, and Mo, especially for the second and third harvests.

According to Dhindsa *et al*. (2016) [15], adding 20% fly ash to clayey soil and 30% to sandy soil enhanced wheat germination, tillering, plant height, life cycle, and grain production. According to Thakare *et al*. (2013) [45], fly ash acts as a great soil modifier, conditioner, and source of vital nutrients for noticeably enhancing the texture and fertility with a notable increase in crop yield. They also found that fly ash at concentrations of 5 to 10% in soil blending was helpful for the development and yield of chilli plants. Singh and Agrawal (2010) [40] carried out an experiment to investigate the effects of applying fly ash on the yield of three different types of mung beans (*Vigna radiata*) on soil that had been improved with varying amounts of fly ash (0, 5, 10, and 20% w/w, respectively). All three of the types evaluated in this experiment showed favorable responses at a 10% application rate. Consequently, it is determined that a lower fly ash treatment dose is a superior choice for increasing the yield of various vegetable varieties. Furthermore, the climate and soil texture at that location also affect vegetable output.

Utilizing fly ash increased the dry mass, root length, and shoot length of *Vigna radiata* and *Sesbania cannabina* (Gupta and Sinha, 2009), as well as the growth and production of cucumbers (Ajaz and Tiyagi, 2003) [2]. Compared to plants cultivated without fly ash, eggplant plants planted in soil modified with 25% fly ash showed a considerable increase in growth and photosynthetic pigments (Khan and Siddiqui, 2017a, 2017b) [21, 22]. Compared to plants planted with 20% sand mix soil and loam soil, carrot plants grown in 20% fly ash adjusted soil exhibited better growth, photosynthetic pigments, and acquired larger amounts of proline. The use of 7.5% fly ash can boost the yield of IR-64 variety rice, according to the findings of a research by Purnamasari *et al*. (2024) [50] that compared several ameliorants, including fly ash applied to peat soil in polybag planting containers. The development of maize and rice was enhanced by soil amended with 60% fly ash, which may also be utilized as a soil-improving resource for plant growth, resulting in the sustainable use of solid waste product (Panda *et al*., 2015) [35].

3.3 Influence of fly ash on metal accumulation in plants

Metal accumulation in plants varies by species as well as within a plant's different components. It was observed that there were significant differences in the way that basil, tomato, zucchini, and sunflower plants absorbed certain metals when they were potted in soil that had been improved with fly ash at rates of 5%, 10%, and 20% (Brake *et al*, 2004) [8]. The absorption rate of As rose in tandem with the fly ash amelioration rates; it was found that the levels of arsenic in basil and zucchini exceeded the hazardous threshold by 7 parts per million.

Cafer *et al*. (2015) [9] evaluated the effects of fly ashes on soil and maize plants. He came to the conclusion that treatments with fly ash also raised the amounts of Na, B, P, S, Ca, Mg, Al, Fe, Cu, Mo, and Se in plant roots. Doses of fly ash treatment were closely correlated with rising element concentrations. Referring to research conducted by Rafiullah *et al*. (2022) [37], *Zea mays* exhibited increased uptake of heavy metals with increasing treatment of coal fly ash. Significant increases in concentration of Cu, Fe, Mn, Ni, and Zn compared to control were observed after applying 60%, 80%, and 100% fly ash treatments. Accumulation of Cd and Pb also increased significantly, indicating that higher concentrations of fly ash improved metal uptake.

The amount of fly ash used has been shown to negatively affect the quality of both soil and rice by increasing the amount of heavy metals available to plants (Singh *et al*., 2016) [41]. While the enzyme systems that provide protection against oxidative stress had higher enzyme activity with the increased application of fly ash, this was not enough to overcome the oxidative stress to rice plants. The buildup of heavy metals in rice indicates a significant risk to food safety and human consumption.

According to Rawat *et al*. (2019) [39], native weed species exhibit a notable buildup of heavy metals originating from fly ash, with different plant species exhibiting distinct accumulation patterns. Generally speaking, metal accumulation was higher in roots than in shoots, while certain species had higher accumulation in shoots. Metal transfer from soil to roots and then to shoots was confirmed by translocation and bioaccumulation parameters.

Tabassum and Singh (2025) [43] assessed the phytoextraction capability of red amaranth, cowpea, moth bean, and malabar spinach and found that, with the exception of Pb, the majority of heavy metals stayed under WHO/FAO limits. Elevated Pb contents in edible plant parts were beyond USEPA carcinogenic risk criteria and allowable limits, suggesting possible issues with human health and food safety.

The findings of Jibrin (2025) [19] showed that heavy metal contamination levels were highest in plants (spinach and moringa) relative to soils and water samples in the study area, and that heavy metal contamination from the ash produced by coal burning processes at a local cement manufacturer played a major role in contaminating crops and water, thus posing a public health and environmental concern.

Conclusion

When fly ash treatment rates are low, higher crop and plant yield will occur due to soil texture being a significant factor affecting agricultural production. However, if fly ash is over-applied, it can create problems for crop production, soil quality, and soil characteristics. Given that metal toxicity is one of the most significant barriers to successfully using fly ash on agricultural land, possible safe usage of fly ash to prevent land and/or watershed contamination exists when fly ash application is conducted under regulated conditions. Regulated fly ash application can reduce the potential for soil erosion and soil degradation, while also providing assistance to maintain healthy ecosystems.

To provide the best prospects for success in applying fly ash in agricultural production, future research should focus on establishing fly ash application guidelines that are regionally based and include a monitoring program to assess the levels of micronutrients and trace metals in soils over time. These activities will aid in the sustainable integration of fly ash into agricultural production systems and will assist in balancing the needs of waste management with the needs of preserving soil health, environmental quality, and food security.

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