13 Management of Fly Ash for Sustainable Soil Health

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13.1 INTRODUCTION

Coal fired thermal power plants contribute to a major portion of the electricity generation in the world. At present, coal is the principal energy source in India, which is used for approximately 62% of electric power generation in the country. This situation will persist for several decades, until alternative sources of energy are developed and exploited on a commercial scale (Ram et al., 2007). The major byproducts of coal combustion at thermal power plants are carbon dioxide, nitrogen oxides, sulfur oxides and air-borne inorganic particles such as fly ash, soot and other trace gas species. Fly ash is the mineral residue resulting from combustion of coal at a high temperature that enters the flue gas streams. Fly ash is an amorphous ferroalumino silicate with a matrix very similar to soil. The elemental composition of fly ash (both nutrient and toxic elements) varies according to types and sources of used coal (Comberato et al., 1997). This has been considered as a problematic solid waste all over the world due to the presence of substantial quantities of trace metals (Cu, Zn, Mn, Mo) and toxic elements like V, Se, As, B, Al, Cd, Pb, Hg and Cr. In India currently 82 coal-fired power plants produce 120 million tons of fly ash per year, and the number is likely to increase to a staggering 600 million tons per year by 2030–31 as per the estimates of Ministry of Power as well as Planning Commission. Safe disposal of this huge quantity of fly ash is a great problem; unlike in countries like Germany, Denmark, France, UK, USA and the Netherlands, where up to 70% of fly ash generated is being used as a building material and for other construction purposes, in India its utilization hardly exceeds 15%. Generally thermal power plants dispose their fly ash either by dumping dry ash in landfills and fly ash basins or by washing out fly ash with water in the form of slurry into ash ponds created for this purpose. Indiscriminate dumping of fly ash in open land has several adverse environmental impacts such as contamination of soil and water with toxic and radioactive elements, land degradation and pollution of air. Construction of ash disposal requires diversion of large area from agriculture/grazing land/habitat leading to land use change and resettlement issues. Additionally, there is a risk of air pollution by increasing the concentration of respirable particulates from fly ash ponds when they remain uncovered. Prolonged exposure to fly ash causes various serious diseases like silicosis, fibrosis of lungs, bronchitis and pneumonitis (Belkin et al., 1999; Finkelman et al., 2000). Movement of soluble leachates from fly ash washed with water significantly influences the surrounding soil, groundwater and surface water. The gradual percolation of soluble heavy metals from unlined ash ponds raises the potential threat of contamination of ground water (Singh et al., 2014).

This warrants devising a suitable management strategy for handling a huge quantity of fly ash and exploring the potential utilization of fly ash in various other sectors. The use of fly ash in agriculture has been considered as a feasible alternative for its safe disposal to improve the soil environment and enhance crop productivity. Studies conducted on fly ash utilization in agriculture and wasteland development indicate that mixing appropriate concentrations of fly ash with soil supplies essential plant nutrients and improves and maintains the soil's physical quality; this can help reclaim wasteland quality and improve agricultural productivity at the laboratory and field. Except organic C and N, fly ash contains almost all the essential plant nutrients i.e. macronutrients including P, K, Ca, Mg and S and micronutrients like Fe, Mn, Zn, Cu, Co, B and Mo. It can also be a cost effective alternative to lime for the reclamation of acid soil. Additionally according to IPCC, agricultural lime application contributes to global warming through the emission of CO_2, and use of fly ash as a soil ameliorant in place of lime could lead to a reduction in CO_2 emissions, thus contributing to the minimization of global warming (Ferreira et al., 2003). Most coal based thermal power plants are concentrated in the eastern part of the country where rice is grown as a predominant crop. Hence, fly ash disposal has a natural preference for rice fields because of its inherent properties like plant nutrient content, high pH and particulate nature for the improvement of soil physical properties. Additionally, the rice soils of eastern India are acidic in nature with problems of restricted internal drainage due to its heavy texture; hence it could be an ideal sink for the disposal of fly ash with additional benefits to the farmers. The addition of fly ash to soil may improve the physic-chemical properties as well as nutritional quality of the soil, and the extent of change depends on soil and fly ash properties (Pandey and Singh, 2010). Fly ash can also be useful for restoration and stabilization of degraded and erosion-prone soils. A great deal of research has been conducted to identify and determine the feasibility of utilizing it in agricultural applications. Concentrated efforts have been put in by all stakeholder agencies like R&D, academia, industry, fly ash generators, facilitators and regulators as well as decision makers since 1994 when Fly Ash Mission (now known as Fly Ash Unit [FAU[, Department of Science and Technology) was commissioned by the Govt. of India with DST as the Nodal Agency. In this paper, the potential use of fly ash as an ameliorant and value added product for reclamation of waste land, improvement of soil quality and productivity has been reviewed.

13.2 FLY ASH AS A SOURCE OF PLANT NUTRIENTS

13.2.1 Physico-Chemical Properties of Fly Ash

Fly ash is often characterized by a number of mineralogical, physical and chemical properties, which are further governed by factors like the nature of the parent coal, conditions of combustion, type of emission control devices and storage and handling methods (Carlson and Adriano, 1993).

Therefore ash produced by burning anthracite, bituminous and lignite coal has different compositions. Fly ash is an amorphous mixture of ferroaluminosilicate minerals generated from the combustion of ground or powdered coal at 400–1500°C (Mattigod et al., 1990). Fly ash generally occurs as ultra-fine particles with an average diameter of <10 μm, with distinctive properties like low to medium bulk density, high surface area and light texture. Further, the fine particles are conjoint into micron and sub-micron spherical particles of sizes varying from 0.01–100 mm diameter (Davison et al. 1974), while the sub-micron particles are entangled by large spheres (Fischer et al., 1976). Fly ash particles are hollow, empty spheres (cenospheres) filled with smaller amorphous particles and crystals (plerospheres). The cenosphere fraction constitutes as much as 1% of the total mass and gets easily airborne. The specific gravity of fly ash ranges from 2.1 to 2.6 g cm^{-3}. Mean particle density for non-magnetic and magnetic particles is 2.7 and 3.4 g cm^{-3}, respectively (Natusch and Wallace, 1974). Bulk density of fly ash varies from 1 to 1.8 g cm^{-3} while the moisture retention ranges from 6.1% at 15 bar to 13.4% at 1/3 bar. Fly ash addition alters the physical properties of soil such as texture, bulk density, water holding capacity and particle size distribution (Sharma, 1989).

Chemically, 90–99% of fly ash is comprised of Si, Al, Fe, Ca, Mg, Na and K with Si and Al forming the major matrix (Adriano et al., 1980). There are mainly two types of ash: Class F (low lime) and Class C (high lime) based on silica, alumina and iron oxide content of fly ash. Al in fly ash is mostly bound in insoluble aluminosilicate structures, which considerably limits its biological toxicity (Page et al., 1979). It is substantially rich in trace elements like lanthanum, terbium, mercury, cobalt and chromium. Many trace elements including As, B, Ca, Mo, S, Se and Sr (Page et al., 1979) in the ash are concentrated in the smaller ash particles. The Fe-oxide content of spheres influences their color, which ranges from water-white to yellow orange to deep red or brown to opaque. Ca was found to be the dominant cation in ESP ash and fly ash collected from dump sites, followed by Mg, Na and K (Maiti et al., 1990). The pH of fly ash varies from 4.5 to 12.0 depending largely on the sulfur content of the parent coal, and the type of coal used for combustion affects the sulfur content of fly ash (Page et al., 1979). Eastern US coals that include anthracite are generally high in S and produce acidic ash, while western US coals, which include lignites, tend to be lower in S and higher in Ca and produce alkaline ash (Page et al., 1979). The coal produced in India is low in S but high in ash content (40%), whereas the coal produced in US is rich in S (2%) and contains only 5–10% ash. Jala and Goyal (2006) studied the chemical constituents of fly ash and showed that it had a relatively low content of major and trace elements (Table 13.1). The solubility of fly ash depends directly on the physicochemical disintegration of the particles, indicating that major portion of total K is localized in the interior glassy matrix while the external glass is enriched with Mg. When the solubility of alkaline fly ash was studied by selective dissolution in mineral acids, it was found that a significant quantity of K occurred in the highly refractory magnetic Fe fraction and that the solubility of Mg in acids was much higher (Green and Manahan, 1978). The variation in the concentration of elements, depending on particle size, is related to combustion conditions and physical and chemical properties of the coal.

13.3 IMPACT OF FLY ASH ON SOIL QUALITY

13.3.1 Soil Physical Properties

The effect of the incorporation of fly ash into soil has been extensively investigated, and the impact of fly ash on soil largely depends upon the properties of the original coal and the soil examined. Fly ash generally has a low bulk density and a high silt fraction particle size distribution. Sandy and clay soils react oppositely while loamy soil is not influenced as significantly in relation to soil-water characteristics. The increase in the silt fractions in sandy soils leads to increased porosity and decreased bulk density. These two in turn decrease infiltration and hydraulic conductivity, and they increase water holding capacity, field capacity and the plant available water. In clay soils the result is decreased porosity and bulk density, increased infiltration and hydraulic conductivity and decreased

TABLE 13.1
Major and Trace Elements in Electrostatic Precipitator Fly Ash[a]

Major Elements	Content (%)	Trace Elements	Content (ppm)	Radio-Active Elements	Radioactivity (Bq/kg)
Al	31.2	As (20–50)	6.2	Ra^{226} (370)	100
Ca	3.4	Cd	1.9	Ac^{228} (2–40)	141
Fe	6.8	Co	58	K^{40} (810–925)	376
Mg	0.14	Cr (10)	330		
Na	0.42	Cu	20		
K	1.08	Mn	739		
S	0.002	Mo (2–40)	4.0		
P	1.08	Ni (50)	13		
N	0.2	Pb (100)	35		
		Se (5–10)	3.6		
		Zn (300)	79		

Source: Jala and Goyal, 2006. Bioresource Technology 97(9):1136–1147.

Note: Values in parentheses ( ) indicate critical levels in soil: Pendias and Pendias (1984).

[a] Unweathered ESP fly ash generated from F grade coal with 40% coal ash (Goyal et al., 2002).

water holding capacity, field capacity and plant available water. Amending sandy and clay soils with fly ash has thus a beneficial effect by increasing plant available water in sandy soils prone to drought stress and alleviating water logged conditions in clay soils by improving drainage. Increasing the silt fraction decreases clod formation in clay soils and improves aggregate formation in sandy soils. The high level of calcium in fly ash enhances flocculation and increases aggregate stability. Enhanced aggregate formation improves soil tilth and seed bed preparation.

Fly ash addition improves the soil's physical properties such as bulk density, porosity and water holding capacity (Sikka and Kansal, 1995; Rautaray et al., 2003; Yeledhalli et al., 2008). The addition of appropriate quantities of fly ash can alter the soil texture by increasing the silt content (Garg et al., 2003). Fly ash addition at 70 t ha^{-1} has been reported to alter the texture of sandy and clayey soil to loamy soil (Fail and Wochock, 1977). The addition of fly ash at 200 t acre^{-1} improved the physical properties of soil and shifted the textural class from sandy loam to silt loam (Buck et al., 1990). Researchers have proved that the particle size range of fly ash is similar to silt, which effectively changes the bulk density of soil and fly ash mixture (Chang et al., 1977). It was observed when fly ash was added in clay soil at 0%, 5%, 10% and 15% by weight it significantly reduced the bulk density and improved the soil structure, which in turn improves porosity, workability, root penetration and moisture-retention capacity of the soil (Kene et al., 1991). Fly ash itself is not effective in retaining water, but it significantly increases the water holding capacity of the soil mixture (Chang et al., 1977). Since fly ash is dominated by silt sized particles, fly ash incorporation exerts a beneficial effect in the soil water holding capacity in sandy soils, as fine textured substances can hold more water than coarse textured substrates (Aitken et al., 1984; Campbell et al., 1983; Gangloff et al., 2000).

Hydraulic conductivity of soils can be improved by the application of limited amounts of fly ash, but it deteriorates rapidly when fly ash input exceeds 20% (v/v) in calcareous soils and 10% in acidic soils (Chang et al., 1977). Fly ash is an inorganic substrate that is rich in electrolytes and does not contain significant organic matter; therefore, its addition to soil results in increased hydraulic activity limited at lower application doses. Application of fly ash at 20 tons per ha reduced the crust strength from 2.39 kg per sq.cm to 1.25 kg per sq.cm (Patil et al., 1996). The impedance of water flow is related to the podzolonic reaction of fly ash, which reacts with water to cement soil particles under wet conditions (Adriano et al., 1980). Fly ash addition leads to increased porosity and a shift in pore size distribution from primarily large macropores to more micropores, which ultimately resulted in increased plant available soil water (Ghodrati et al., 1995; Aitken et al., 1984; Adriano and Weber, 2001).

13.3.2 Soil Chemical Properties

Fly ash, which can be acidic or alkaline depending on the source, can be used to buffer the soil pH (Phung et al., 1978). The alkaline fly ash can be added to increase the pH of acidic soils; it can also act as a soil modifier to upgrade the physical properties and improve the texture, upgrade the chemical and biological quality of soil (increase in cation exchange capacity, capacity of water retention, nutrient availability) and thus participate in the optimization of plant growth (Chang et al., 1977; El-Mogazi et al., 1988). The initial increase in soil pH after the alkaline fly-ash amendment is explained by the rapid release of Ca, Na, Al and OH^- ions from fly ash (Wong and Wong, 1990). In India, most of the fly ash produced is alkaline in nature. Hence, an application of this to agricultural soil increases the soil pH. This property of fly ash can be better exploited to neutralize acidic soils (Phung et al., 1978). The addition of fly ash is reported to improve soil pH, with an additional benefit to supplement essential plant nutrients in soil (Jastrow et al., 1979). Page et al. (1979) observed that experiments with calcareous and acidic soil revealed that fly ash addition elevated the pH of the former from 8.0 to 10.8 and of the latter from 5.4 to 9.9. It must be noted here that the use of excessive quantities of fly ash to alter pH can cause an increase in soil salinity, especially with un-weathered fly ash. The fly ash-water interaction in the applied field in due course leads to the development of an incrustation of polysilate on ash particle surface imparting exchangeable capacity for cations and anions (Sahu, 1989). As a result of hydrolysis of CaO and MgO, the application of fly ash increased the pH of the soil, which is beneficial on acidic soils. Jena et al. (2005) showed that application of fly ash from Angul Power Plant (Odisha) corrects ion toxicity, which is a common soil limitation in low pH lateritic soils of Orissa. Another study revealed that in a fly ash application of up to 20% an increase in micronutrient availability was noticed, while beyond that fly ash led to an accumulation of toxicmetals (Zn, Fe, Cu, Mn, Cd, Cr) in agricultural soils (Nayak et al., 2015). Moreover, the C mineralization rate is also suppressed in soils treated with 10%–20% fly ash from day 7 to day 120 in an incubation study performed indicating the possibility of soil C sequestration (Nayak et al., 2014). So in a nutshell, application of fly ash influences almost all vital soil chemical properties and establishes its impact in soil quality. However, heavy metal toxicity is often raised against the use of fly ash, which has to be taken care of by fixing the permissible dose.

13.3.3 Soil Biological Properties

Not much elaborate information is available on the effects of fly ash amendments on soil biological properties. Several short-term laboratory incubation studies found that the addition of un-weathered fly ash to sandy soils severely inhibited microbial respiration, enzyme activity and soil nitrogen cycling processes such as nitrification and N mineralization (Garau et al., 1991). Some factors such as pH, salinity, toxicity of B and other trace elements and poor physical conditions can limit the colonization of microorganisms as well as plants in the fly ash (Carlson and Adriano, 1993). The most limiting factors for microbial activity are usually a lack of substrate C as an energy source for heterotrophic microorganisms and also the lack of an adequate N supply (Klubek et al., 1992). However, earlier studies indicate that the microbial diversity generally increases as ash weathers and nutrients accumulate.

Elevated populations of arbuscular mycorrhizal fungi (AMF) (Schutter and Fuhrmann, 2001) and diazotrophs and phosphobacteria (Gaind and Gaur, 2003) have been reported in fly ash applied soil. The enzymatic activity of soil is also an important factor for measuring soil biological properties after the fly ash amendment is in soil. It has been found that a significant increase in the rate of CO_2 evolution and the activity of soil enzymes (protease and dehydrogenase) in fly ash amended soil from a pot culture experiment. Increases in enzyme activity and CO_2 evolution in soil have been reported as favorable for soil microbial activity. It was reported that no signifiacant inhibition of soil respiration and enzyme activities was found in up to 2.5% fly ash amendment. In that situation further addition of fly ash caused a decrement of above-mentioned microbial activities. On the other hand, significant stimulation of soil respiration and microbial activities was observed in up to 5% fly ash amendment when the soils contained earthworms. Both fluorescein diacetate assay and denitrifiers showed an increased trend up to application of fly ash at 40% but with a concomitant decrease in alkaline and acid phosphatase activities (Nayak et al., 2015).

Nayak et al. (2014) highlighted that microbial biomass C (MBC) in 0.5%–5% fly ash treated soils increased significantly in the initial phase (up to 30 days), thereafter decreasing, while the application of 10% and 20% fly ash treated soils showed a decreasing trend of soil MBC with time, which is in accordance with the soil C mineralization pattern as well. The researchers further emphasized that soil heterotrophic microbial populations, as represented by both above mentioned parameters, is negligibly affected by low (up to 2.5%) doses of fly ash amendment but, when applied at higher doses (10% or 20%), soil microbial activity is hampered.

The application of unweathered fly ash, particularly to sandy soil, inhibited the microbial respiration, enzymatic activity and soil N cycling processes like nitrification and N mineralization (Wong and Wong, 1986; Garau et al., 1991), and adverse effects were caused by the presence of excessive levels of soluble salts and trace elements in un-weathered fly ash. The use of extremely alkaline (pH 11–12) fly ash could also be the reason for those adverse effects. However, natural leaching and the slow process of weathering often reduced the detrimental effects over time.

Fly ash has also showed its positive role in controlling soil borne plant diseases. The application of lignite fly ash reduced the growth of seven soilborne pathogenic microorganisms (Karpagavalli and Ramabadran, 1997). The population of both fungi and actinomycetes decreased with the application of fly ash (Nayak et al., 2015).

13.4 POTENTIAL UTILIZATION OF FLY ASH AS SOIL AMENDMENTS

13.4.1 Fly Ash for Improving Soil Fertility

The majority of crops prefer optimum pH values of between 6.5 and 7.0, within which the availability of most nutrients to plants is maximized. Fertility is impaired at very low pH levels, as dissolution and bioavailability of Mn and Al that are toxic to plants increases; similarly at very high pH, the crop plants are unable to take up most of the essential nutrient elements. The alkaline and acidic fly ash can be used to improve the soil pH and it bring to a normal condition where the availability of nutrients is optimum. Both the electrical conductivity (EC) and metal content of soil increases with fly ash application. Lime in fly ash readily reacts with acidic components in soil and releases nutrients such as S, B and Mo in the form and amount beneficial to crop plants. Fly ash has been used for correction of sulfur and boron deficiency in acid soils (Chang et al., 1977).

Application of fly ash for improving the nutrient status of soil has been reported by Rautaray et al. (2003). Fly ash collected directly from a thermal power station by electrostatic precipitators in Bathinda, India was found to be finer in texture, lower in pH and generally richer in nutrients than the ash collected from the dumping sites (Sikka and Kansal, 1994). Major matrix elements were found to be Al and Si, together with significant percentages of K, Fe, Ca and Mg. The saturation moisture percentage of both the ashes was higher, but the bulk density was lower than the normal cultivated soils. Calcium was present as the dominant cation on the exchange complex followed by Mg^{2+}, Na^+ and K^+ in addition to high sulfur content.

The ability of Ca to enhance flocculation/aggregation of soil particles, particularly clay, keeps the soils friable, enhances water penetration and allows roots to penetrate hard/compact soil layers. Calcium readily replaces Na at clay exchange sites to enhance soil flocculation and stability. An appreciable change in the soil physicochemical properties, rising of pH and increased rice crop yield was obtained by the mixed application of fly ash and paper factory sludge and farmyard manure (Molliner and Street, 1982). Co-utilization of a mixture of fly ash, sewage sludge and lime in the ratio of 60:30:10 had a beneficial soil ameliorating effect (Reynolds et al., 1999). Incorporation of fly ash in soil had positive effects on soil pH and Ca, Mg and P content and reduction in the translocation of Ni and Cd (Rethman and Truter, 2001) and enhanced growth and yield of corn, potatoes and beans in pot trials.

13.4.2 FLY ASH FOR IMPROVING CROP PRODUCTION

Fly ash may play the role of a good soil ameliorant for improving crop production by providing a ready source of plant-available macro and micro nutrients and improving the physical, chemical and biological properties of problem soils (Jala and Goyal, 2006). The yield of crops grown with fly ash applied soil (10–200 ton per ha) increased by 10–40% depending on the soil types and the nature of the fly ash used. Thus the use of fly ash in agriculture has proved to be economically rewarding (Kalra et al., 1997; Singh et al., 1997; Vimal Kumar et al., 2005). The crop response appeared to depend on a combination of factors such as method of application, physicochemical properties of soil, precipitation and plant species. In the case of rice, only a few studies have been made at an international level (Lee et al., 2006).

A field experiment involving rice-rice cropping sequence under irrigated conditions during wet (cv. Gayatri in June–November 2010) and dry (cv. Lalat in January–May 2011) season at Central Rice Research Institute, Cuttack, India was conducted to evaluate the efficacy of fly ash as a soil ameliorant and nutrient source for rice based cropping system. The treatments were arranged in a randomized complete block design with three replications comprised of different combinations of fly ash, FYM and chemical fertilizers. The application of lime, fly ash and FYM was a one time application and has not been applied for the second crop i.e. dry season. Bulk application of fly ash had a profound effect on the rice yield, and the magnitude of response varied with the quantum of fly ash applied either alone or in combination with FYM and inorganic fertilizers. The application of fly ash alone at 50 t ha^{-1} has resulted in on par yield with that of farmers' practice and significantly lower yield than the 100% RDF during the wet season while in the succeeding dry season, rice yield under FA_{50} plots was significantly lower than the yield obtained from farmers' practice (Nayak et al., 2011). However, application of fly ash at 50 t ha^{-1} along with 75% RDF and 25% through FYM on N basis has recorded on par yield with that of Lime + 100% RDF in both wet and dry seasons. Excess application of fly ash alone (at 100 t ha^{-1}) has reduced the rice yield significantly *vis-à-vis* farmers' practice in both the seasons while the combined application of fly ash (at 50 t ha^{-1}) and FYM (at 12.5 t ha^{-1}) has produced on par rice yield with that of farmers' practice in both the seasons (Table 13.2).

The application of fly ash (10 t ha^{-1}) combined with other organic manures (paper factory sludge, farm yard manure and crop residues), along with chemical fertilizers, showed a remarkable increase of the grain yields of rice by 31%, pod yield of peanut by 24% and equivalent yield of both the crops by 26%, as compared to the use of chemical fertilizer alone (Mittra et al., 2005). Based on the field demonstration projects conducted at more than 50 locations by Fly Ash Mission (FAM), now known as Fly Ash Utilisation Programme (FAUP), in varying agro-climatic conditions and different soil-crop combinations supported with laboratory investigations, Kumar et al. (2005) reported a significant increase in yields of the edible part and crop biomass without showing any adverse impact on soil health or crop produce, due to the presence of trace heavy metals and radionuclides in fly ash, and opined that the large scale use of fly ash in agriculture holds a good potential to increase on an average 15% yield of grains, oil seeds, sugarcane, cotton and about 25–30% yield of vegetables (Velayutham and Jha, 2009).

Yeledhalli et al. (2008) studied the long term effect of bulk application of fly ash/pond ash at 30–40 t/ha with the recommended dose of NPK fertilizers alone or along with FYM at 20 t/ha for the cultivation of sunflower maize crops in irrigated vertislos in rotation. The results indicated that the total yield of 35.7 q/ha was recorded in treatment receiving pond ash at 40 t/ha along with FYM at 20 t/ha, which was a 53% increase over control. The water holding capacity of the soil increased

TABLE 13.2
Effect of Fly Ash Application on Yield and Economics of Transplanted Rice

	Wet Season 2010		Dry Season 2011	
Treatment	**Yield ($t\ ha^{-1}$)**	**B: C Ratio**	**Yield ($t\ ha^{-1}$)**	**B: C Ratio**
FP[a] (40:20:0 kg N:P:K ha^{-1})	4.37	2.29	4.02	2.03
RDF[b] (80:40:40 kg N:P:K ha^{-1})	5.23	2.55	4.85	2.29
Lime + RDF	5.90	1.41	5.28	2.59
Fly ash @ 50 t ha^{-1} (FA_{50})	4.07	2.44	3.14	1.65
Fly ash @ 100 t ha^{-1} (FA_{100})	3.73	2.15	2.83	1.39
$FA_{50} + RDF_{75\%} + FYM_{25\%}$[c]	5.45	2.59	4.98	2.56
$FA_{100} + RDF_{75\%} + FYM_{25\%}$	5.17	2.40	4.64	2.32
FA_{50} + FYM @12.5 t ha^{-1}	4.81	2.18	3.67	2.10
FA_{100} + FYM @12.5 t ha^{-1}	4.20	1.78	3.06	1.58
LSD ($p = 0.05$)	0.601	–	0.534	

[a] Farmer's practice.

[b] RDF: Recommended dose of fertilizer.

[c] $FYM_{25\%}$: 25% of RDF through farm yard manure on N basis.

from 64 to 67.5% due to pond ash at 40 t/ha application, while there were only marginal changes in soil physico-chemical properties with respect to either fly ash or pond ash application. Ram et al. (2007) also reported an increased yield of groundnut, maize and sunhemp with lignite fly ash application. Fly ash could also be able to increase the leaf area index, root length density and grain yield of wheat (Garg et al., 2005). On the contrary, a significant reduction in rice grain yield to the tune of 12.3, 15.7 and 20.2% was recorded over control when fly ash was dusted at 0.5, 1.0 and 1.5 g m^{-2} day^{-1}, respectively, due to increased heat load on canopy and reduced intercellular CO_2 concentration (Raja et al., 2014).

A high yield of aromatic grasses, particularly palmarosa (*Cymbopogon martini*) and citronella (*Cymbopogon nardus*), in the presence of different fly ash-soil combinations was attributed to increased availability of major plant nutrients (Neelima et al., 1995). Fly ash applied at 25% showed a higher yield of brinjal (*Solanum melongena*), tomato and cabbage. Oil seed crops such as sunflower (*Helianthus* sp.) and groundnut (*Arachis hypogaea*) also responded favorably to a fly ash amendment. Medicinal plants such as cornmint (*Mentha arvensis*) and vetiver (*Vetiver zizanoides*) were successfully planted in fly ash used in conjunction with 20% farmyard manure (FYM) and mycorrhiza (Sharma et al., 2001).

Velayutham and Jha (2009), while compiling the results of the fly ash application in varying crops in varying locations, reported the following results. In alluvial loam soil of the Murshidabad district of West Bengal, better germination and growth in respect to height, tiller and crop yield of both paddy and wheat grown in all doses of dry fly ash and pond ash were observed. In alkaline soil the effect of fly ash was found to be more pronounced in wheat than paddy. A one time application of pond ash at 200 t/ha and recommended dose of NPK increased the yield of wheat by 43.3% and paddy by 16.9%. In a field trial with 100 t/ha pond ash and NPK, the yield of wheat increased by 46.7%. In mustard wheat jute crop rotation, the increase in the percentage of yield of jute (19.5%) is more than mustard (11.84%) and wheat (9.37%). A significant residual effect of dry fly ash and pond ash was observed with 100t/ha application of ash.

Wheat, paddy and cotton grown in the alluvial (loam sand) soil of Punjab responded to the application of fly ash rates as high as 80 t/ha and recommended dose of NPK. With respect to the cotton crop, which was grown in rotation, pond ash at 20 t/ha was applied along with a recommended dose of NPK. In a large scale demonstration held in Maharashtra in clayey soil with 174 farmers and crops, it was noticed that with a pond ash dose of 10t/ha and with a recommended dose of fertilizers, the percentage increase in the yields of crops were paddy (12.2), cotton (17.4 to 22.7), bajra (15.2 to 25), groundnut (18.5 to 25), jowar (9 to 20.5), sunflower (28), sesamum (7.7) and urad (12). In the experimental farm in Bijwasan, Gurgaon, Haryana, 25 t/ha pond fly ash in the rice-wheat rotation with a recommended dose of NPK increased the yield of both the crops significantly, in red lateritic soil. The yield of paddy was 62 q/ha and wheat was 46.3 q/ha. This represents an increase over control at 11% and 10% respectively.

13.5 FLY ASH: AN AGENT OF ENVIRONMENTAL MANAGEMENT

13.5.1 Stabilization of Heavy Metal-Contaminated Sites

Fly ash is added to the soil to reduce metal mobility and availability in soil and help to restore soil properties. The mechanism of immobilization involves the phenomenon of adsorption, complexation and (co)precipitation. Synthesized zeolites from FA have been used in the immobilization of heavy metals in polluted soils; fly ash is an alkaline waste material with a high sorptive capacity, which increases the surface area available for element adsorption and renders most cationic metals less mobile (Ciccu et al., 2003).

13.5.2 Bioremediation

Recently, bioremediation of heavy metals with fly ash is an alternate emerging technology, which is more self-sustainable, cost effective and eco-friendly than existing conventional methods. Phytoextraction takes several years to remove metals from contaminated soils due to low bioavailability of metals (Denuex-mustin et al., 2003). To overcome this problem, various synthetic chelates like EDTA have been used to induce metal bioavailability, but their biodegradability is very low in comparison to microbial chelates. Hence, they may be toxic to plants. Most of the bacterial strains either induced the bioavailability of Fe, Zn and Ni or immobilized Pb, Cr, Cu and Cd in the fly ash (Tiwari et al., 2008).

13.5.3 Restoration of Degraded Lands

Sometimes soil loses fertility and quality due to environmental causes and unmanaged exploitation by humans. For increasing soil productivity, waste fly ash could be used as an exploitable resource for the management of degraded soils, because FA possesses several similarities to soil and contains essential micro-nutrients (Fe, Mn, Zn, Cu, Co, B and Mo) and macro-nutrients (P, K, Ca, Mg and S) (Pandey et al., 2009). Fly ash also can be used in the reclamation of wastelands (sodic soil, acidic soil and mine spoil), as FA possesses many of the functional properties of lime and gypsum.

13.5.4 Curb Global Warming

Agricultural lime contributes in the global fluxes of the greenhouse gases such as carbon dioxide, nitrous oxide and methane. Much research revealed that additional opportunities have arisen for lessening the global warming potential by altering agronomic practices (Robertson et al., 2000). According to the Intergovernmental Panel on Climate Change (IPCC), agricultural lime application contributes to global warming through the emission of CO_2 to the atmosphere; the US EPA estimated that 9 Tg (teragram = 1012 g = 106 metric tons) of CO_2 was emitted from an approximate 20 Tg of applied agricultural lime in 2001. Some researchers have been working on the utilization of FA in place of agricultural lime for minimizing global warming. An experimental study revealed that 1 ton of FA could sequester up to 26 kg of CO_2, i.e. 38.18 tons of FA per ton of CO_2

sequestered. This study confirmed the possibility to use this alkaline residue for CO_2 mitigation (Montes-Hernandez et al., 2009). So, use of FA instead of lime as a soil ameliorant can reduce net CO2 emission and thereby lessen the potential risk of climate change.

13.5.5 Fly Ash: A Versatile Waste Product

Several potential applications of fly ash are as follows: fly ash is being used in the ceramic industry (Jonker and Potgieter, 2005), concrete and cement manufacturing industries (Gao et al., 2008), in the removal of chemical oxygen demand (COD) from textile mill effluents (Patnaik et al., 1995), seepage control through various hydraulic structures (Gupta and Alam, 2004), synthesis of zeolites (Moreno et al., 2002), as a pesticide (Sankari and Narayanasamy, 2006, 2007), additives for the immobilization of industrial and water treatment wastes (Dirk, 1996), removal of mercury and lead ions from waste water (Somerset et al., 2008), copper removal from aqueous solution (Kapadia et al., 2000), as an effective low cost adsorbent for the removal of heavy metal ions from municipal solid waste leachate (Mohan and Gandhimathi, 2009) and as reservoirs for valuable metals, such as Al, Si, Fe, Ge, Ga, V and Ni (Font et al., 2001).

13.6 POTENTIAL RISK ASSOCIATED WITH FLY ASH APPLICATION

Generally the fly ash is applied to the agricultural fields in huge quantities because of its low bulk density and low nutrient contents. Besides this, fly ash is also used for land filling in the low lying fields, which are subsequently used for agriculture and forestry purposes; application at such high rates may negatively affect the biological and chemical properties of the soil, leading to a negative impact on crop growth, human health and environment.

The major concern of fly ash application in agriculture is the presence of many potentially toxic elements such as As, Cu, Zn, Cd, Pb, Co, Mo, Mn, Hg, Ni, Cr, Se, B, etc. and associated risk in humans and animals through its consumption (Yunusa et al., 2012). The extent of heavy metals in fly ash depends on both the mineralogy and particle size distribution of the raw material being burnt and the combustion temperature of fly ash. In another study, Praharaj et al. (2002) has observed that groundwater in the vicinity of the ash pond in the Angul district of Odisha (India) is contaminated with heavy and toxic metals like Fe, Ba, Cu, Mn, S, Pb, V and Zn. This is due to the very high leachability of many trace elements from fly ash by the infiltrating rainwater. Studies show that 5–30% of heavy metals present in FA are leachable (Ram and Masto, 2010; Singh et al., 2010), and these metals can be leached from soils, especially when it is applied in a high rate leading to the pollution of land, groundwater, rivers and lakes. However, the extent of contamination depends on the mobility of heavy metal. and the amount of heavy metals released from fly ash depends largely on the pH, bonding between the element and fly ash and its chemical form (Pandey, 2014). In a laboratory column leaching experiment Wang et al. (2008) observed that the concentrations of Ni, Co, As, Cd, Mo and U in leachate exceeded the permissible limits when FA containing column was exposed to simulated acid rain. Verma et al. (2016) reported that the heavy metal concentration in groundwater collected from villages adjacent to the Parichha thermal power plant in Jhansi, India was Pb (0.170–0.581 ppm), Ni (0.024–0.087 ppm), Fe (0.186–11.98 ppm), Cr (0.036–0.061 ppm) and Mn (0.013–0.178 ppm), and the range exceeded the value of heavy metals prescribed by WHO for groundwater.

Though fly ash improves physicochemical characteristics of soil and provides various essential elements to plants, its application beyond a certain limit may have direct and indirect adverse effects on soil quality, crop growth and human health. Poor or no availability of nitrogen, phosphorus and organic carbon in fly ash may affect protein and amino acid metabolisms and disrupt energy flow in cells, growth and development, as well as decrease resistance against plant diseases (Basu et al., 2009). In a study on the effects of fly ash on soil health, plant growth, toxic metal accumulation and antioxidant responses in rice, Singh et al. (2016) observed that the application of fly ash at a rate of

50% resulted in a reduction in soil enzymatic activities and decreased the root, shoot and panicle length and augmented sterility in rice. Lipid peroxidation was also increased in the root and shoot of fly ash treated plants, indicating oxidative stress. Additionally, the accumulation of toxic metals, particularly Cd, Cr, Pb and As, was 14–15 fold higher in the roots and shoots and 4–20 fold higher in the grains with fly ash application as compared to normal garden soil, and human associated risk analysis revealed that the calculated maximum tolerable daily intake values for toxic metals *viz*. Cr, As, Cd, Hg and Pb was beyond the safe limit.

Repeated application of fly ash may lead to the accumulation of heavy metal in soil leading to uptake by the crop. Elevated concentrations of heavy metals in the edible part of the crop will again pose a serious threat to human and animal health. The study indicated repetitive application of fly ash at the rates of 20–30% over the years considerably altered plant metabolism and resulted in degraded soil health and more availability of toxic metal (Narayana et al., 2010). Fly ash application reportedly affects microbial and enzymatic activities as well as the process of N cycling such as nitrification and N mineralization in soil (Pitchel and Hayes, 1990; Kumar et al., 2012); Nayak et al. (2014) reported that fly ash applied at a rate of 40% led to the accumulation of toxic metals in the soil and suppressed the microbial growth and activity. When added at a higher rate, a lack of C substrate, inadequate N supply and high content of toxic heavy metals in fly ash can hinder normal microbial metabolic processes in the soil.

Fly ash also contains various radioactive elements such as ^{238}U, ^{232}Th, ^{40}K, ^{226}Ra, ^{210}Pb, ^{228}Ra, etc. Concentrations of different radio nucleotides in the fly ashes is generally higher than the parent coal used for consumption and the enrichment factor; the enrichment factors ranged from 0.60 to 0.76 for ^{238}U, from 0.69 to 1.07 for ^{226}Ra, from 0.57 to 0.75 for ^{210}Pb, from 0.86 to 1.11 for ^{228}Ra and from 0.95 to 1.10 for ^{40}K (Papastefanou, 2008). However, due to the highly dangerous nature of these pollutants with respect to their effect on living organisms, a cautious approach is needed for using fly ash in agriculture.

Weathered fly ash contains a higher level of soluble salt, and its application as an additive to soil can increase the salt content. Apart from that, the leaching of soluble salts and other ions Ca^{2+}, Na^{+}, F^{-}, Cl^{-}, SO_4^{2-}, OH^{-} and CO_3^{2-} from fly ash can increase the salinity and hardness of the nearby water reservoir and ground water (Ram and Masto, 2010).

13.7 CONCLUSION

There is an ample scope for safe utilization of different industrial wastes including fly ash in combination with chemical fertilizer for improving soil fertility and augmenting yield. Thus, fly ash can be safely incorporated as a soil ameliorant and also a rich source of secondary (Ca, Mg) and micronutrients, particularly in acidic soil. Such utilization of industrial waste in an integrated manner can be a win-win strategy to save chemical fertilizers to a significant extent; and also to curb the environmental pollution load in terms of indiscriminate deposition of industrial wastes. Overall, the beneficial effects of fly ash can be highlighted as: (i) improves soil texture; (ii) reduces bulk density of soil; (iii) improves water holding capacity; (iv) optimizes pH value; (v) increases soil buffering capacity; (vi) improves soil aeration, percolation and water retention in the treated zone (due to dominance of silt-size particles in FA); (vii) reduces crust formation; (viii) provides micro-nutrients like Fe, Zn, Cu, Mo, B, etc.; (ix) provides macro-nutrients like K, P, Ca, etc.; (x) reduces the consumption of soil ameliorants (fertilizers, lime); (xi) has insecticidal purposes; (xii) decreases the metal mobility and availability in soil; while also taking into consideration its possible harmful effects: (i) reduction in bioavailability of some nutrients due to high pH (generally from 8 to 12); (ii) high salinity; (iii) high content of phyto-toxic elements, especially boron. However, further research is required on a wide range of field crops and horticultural crops for harnessing the potentiality of fly ash. That may in turn help in deciding whether fly ash can be suitably extended for farmers' field for ensuring better soil quality, crop productivity and cost effectiveness.

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