

Mathematical Analysis of the Effect of Fly Ash Application in Agricultural Fields on Soil Properties and Crop Productivity

Mamta Verma¹, Kirti Verma^{2,*}

Abstract

Fly ash is regularly generated as a by-product by coal or thermal power stations. The potential of fly ash as a resource material in agriculture and related areas is now a well-established fact. The application of fly ash in agriculture is due to its favorable physicochemical properties, including appreciable content of essential plant nutrients. When compared to soil, fly ash consists of all the elements except organic carbon and nitrogen. The purpose of this paper is to provide an overview of the characterization and utilization of fly ash in agriculture. The effects of fly ash on soil properties, improvement in crop yields, and heavy metal uptake by plants were mentioned. The purpose of this paper is to explore the possibility of fly ash addition into degraded soil for improving nutritional and physicochemical properties.

Keyword: Fly ash, wasteland soil, enzyme activity, heavy metal, micro- and macronutrients

INTRODUCTION

Industrial power plants produce millions of tons of solid waste every year, which includes mainly municipal waste, thermal waste, waste from mines, etc. Every year in India, thermal power waste (fly ash) itself includes 60 million tons [1]. Fly ash is obtained during the combustion of coal in coal-fired plants at 1350–1650 °C for power generation. Depending on the starting coal and operating conditions, kiln fly ash has different physical, chemical, and mineralogical compositions [2].

Generally, these wastes are disposed of in the lands where they occupy large fertile areas and induce bad effects in groundwater, thereby worsening the living environment directly or indirectly [3]. Presently, 5% of total ash is used in road embankments, coatings, ceramics, and as a starting material in the preparation of civil construction components like cement and concrete blocks due to the pozzolanic property of fly ash [3]. A large portion remains unutilized, causing concern to environmentalists, the public, and government officials. The major field where a bulk quantum of fly ash can be utilized is in agricultural land, which was considered after evaluating the physicochemical characteristics, which reveal the presence of various mineral constituents and its excellent ameliorating property.

Fly ash, for its abundant availability and, in addition, due to its ameliorating property and as a good source of nutrients, imparts the demand for an inexpensive product management technology for its fruitful utilization. This integrated research will open up new ways to improve soil potential while increasing agricultural productivity and protecting the environment from harmful hazards.

*Author for Correspondence

Kirti Verma
E-mail: vermalkirti18@gmail.com

¹Associate Professor, Department of Civil Engineering, Bansal College of Engineering, Mandideep, Bhopal, Madhya Pradesh, India

²Associate Professor, Department of Engineering Mathematics, Gyan Ganga Institute of Technology and Sciences Jabalpur, Madhya Pradesh, India

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Therefore, the purpose of this study was to focus on the chemical reactions that occur between soil and fly ash in artificial media prepared by mixing different proportions of fly ash into black cotton soil (clay) to assess plant growth. Its release leads to the movement of nutrients in the soil.

MATERIALS AND METHODS

Black cotton (clay) under investigation was collected from Bhopal, MP, and fly ash from MPEB, Sarni, India. Soil and fly ash samples were collected arbitrarily subsequent to the typical method of quarter and cone [4] from every sector under study, air-dried, and stored at room temperature. The properties of clay soil, fly ash, and fly ash-admixed soil were detected in terms of texture [5], water-holding capacity, porosity, density, pH (determined potentiometrically using a glass calomel electrode system in a 1:2 soil-water ratio), and conductivity [6]. The results of these studies are depicted in Table 1A. The available plant nutrients in clay soil were determined in different test media by adopting standard methods. NO₃-N was determined by Kjeldahl's method [7], PO₄ by NaHCO₃ extraction, K by ammonium acetate [7], Ca and Mg were estimated titrimetrically with EDTA [8], SO₄ colorimetrically [9], and Cu, Zn, Pb, and Fe by DTPA extraction. The mineral phases of clay soil and fly ash were identified by applying the diffractometric technique by operating a Philips X-ray machine PW1710. The data obtained were interpreted by the ASTM card index and are cited in Table 2.

Pot experiments were conducted to investigate the growth of soybean (*Glycine max*) in artificial soil mix produced by alkaline fly ash in sandy and clay soil. To carry out the experiments in triplicate, fly ash was mixed thoroughly with both the soils in various percentages (0, 10, 20, 30, 40, and 50% w/w) and then packed in pots of identical dimensions. For physicochemical and mineralogical studies, nearly 100 g of each soil sample was collected from every pot before sowing, air-dried, ground, and then passed through a 2 mm sieve. Equal numbers of seeds/plants were sown/transplanted in both cases, control and artificial soil. Fertilizers and pesticides were applied identically in all cases for comparison. The pots were watered daily by a calculated amount of water. The seedlings were permitted to cultivate to maturity and then harvested.

RESULTS AND DISCUSSION

Physical Constraints: Texture, porosity, density, and water-holding ability

Clay Soil

Table 1A indicates the results of the density, porosity, and water-holding capacity of clay soil, fly ash, and soil admixed with fly ash. In the present study, the texture of the control soil was clay (fine-textured), and thus the density of the soil is more (1.3). The porosity was low (45.5%) as the particles are compactly arranged, causing less infiltration. The water-holding capacity is high (60%), which ultimately leads to a waterlogging problem. The results correlate with the work reported earlier [10]. In addition, clay soils have high tenacity; this reduces the availability of nutrients to the plants, resulting in the wilting of crops. On admixing different percentages of ash with soil, there was a remarkable change in the physical properties of soil as compared to the control. It was observed that as the fly ash composition increased in the soil, the density had reduced from 1.3 to 1.1. Porosity had increased from 45.6 to 52%, and water-holding capacity had reduced from 60 to 58%. The marked change was mainly because of the silty character of fly ash, its stumpy density (0.99), superior porosity (50%), and other corporeal circumstances.

pH and Conductivity in Clay Soil

Table 1A shows that pH increased with the increase in ash percentage in soil. This can be explained simply by the increase in CaO and MgO in the fly ash-admixed soil, which was contributed from the alkaline fly ash added and also for the neutralization of H⁺ ions by more basic metallic oxides of fly ash. The observations correlate with the earlier work reported by [11].

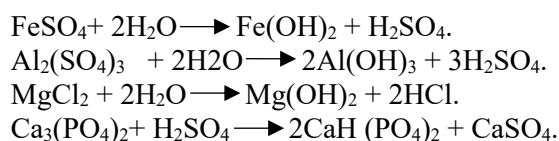
AVAILABLE PLANT NUTRIENTS IN CLAY SOIL

Primary and Secondary Nutrients

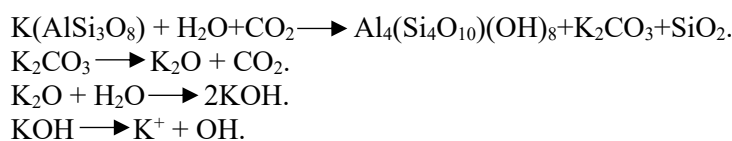
Tables 1 and 2 indicate the results of primary and secondary nutrients, and Tables 3 and 4 indicate the micronutrients in different percentages of fly ash in clay and sandy soil. It indicates that in clay soil, optimum availability of primary and secondary nutrients was in 30% fly ash and in sandy at 20% treatment. The availability of micronutrients is found to increase with the increase in dose of fly ash.

The combination of texture, density, porosity, water-holding capacity, pH, microbial activity, and ionic reactions, in which the components of both combine together in a positive way through a series of chemical reactions and lead to the release of the nutrients in the ionic form, was what made the nutrients most readily available. This helps to condition the soil medium and increase the concentration of nutrients so that plants can absorb nutrients according to specific physiological mechanisms. The results are also strengthened by the X-ray studies which are reported in Table 5. The amount of nitrogen present was calculated using NO₃⁻. The higher availability of NO₃⁻ at low rates of fly ash could be due to the additional organic carbon supplied by fly ash which enhances the biogeochemical cycles [12]. In addition, at a higher dose of fly ash, a decline in NO₃⁻ was observed. This could be attributed due to the inhibition of microbial activity posed by available toxic metals released by fly ash at a higher dose due to an increase in pH. A similar pattern was seen with phosphate. The extra phosphorus in fly ash may be to blame for the rise in concentration.

This range is considered as nontoxic for microbes responsible for the transformation and solubilization of the inorganic PO₄ into the available form. Plants take PO₄ in HPO₄⁻ form [13]. The increase is due to the hydrolysis of Fe, Al, and Mg compounds in fly ash which finally release the inorganic acids. Since the organic matter present in the soil has a buffering capacity to maintain pH, the acid released helps release available phosphates from non-available forms without affecting pH. The reactions that occur to liberate phosphate from unusable to usable forms are explained as follows:



K⁺ is the unit of measurement for potassium. It can be found as albite and mizzonite in fly ash and soil. According to [14], the complex elements present likely undergo changes controlled by a variety of variables such as pH, moisture, cation exchange, microbial activity, etc. The proposed mechanism behind the release of ions in the ionic form is summarized below. This aids in the release of ions in a similar form and contributes to the soil.



Higher amounts of fly ash lead to mineral conversion, but lower K availability due to lower clay content and cation exchange capacity.

Table 1. Physical properties of clay soil and fly ash mixed clay soil.

Parameters	PS	FA	PS+A	PS+B	PS+C	PS+D	PS+E
Texture	Clay	Silty	Clay	Silty clay	Silty clay loam	Silty loam	Silty loam
Water Holding Capacity	60	58	60	59.5	59	59	58
Porosity (%)	45	55	46	48	49	50	52
Density gm cc-1	1.3	0.99	1.28	1.28	1.27	1.25	1.19
pH	8.02	7.3	8.02	8.34	8.4	8.3	8.38
Conductivity uhmos cm-1	137	185	119	129	132	138	140

Table 2. Physical properties of sandy soil and fly ash amended soil.

Parameters	PS	FA	PS+A	PS+B	PS+C	PS+D	PS+E
Texture	Sandy	Silty	Sandy	Silty loam	Silty loam	Silty	Silty
Water Holding Capacity (%)	25	58	26	27.8	30	32.5	35
Porosity (%)	30	55	32	34	38	42	45
Density gm cc-1	1.3	0.99	1.3	1.28	1.25	1.22	1.21
pH	6.84	7.3	6.9	7.12	7.15	7.15	7.15
Conductivity (hmos cm-1)	99	185	102	110	119	122	138

PS = Pure soil FA = Flyash.

A = 10% B= 20% C = 30% D = 40% E= 50%.

Table 3. Available plant nutrients in clay soil and fly ash amended soil.

Element	PS	FA	PS+A	PS+B	PS+C	PS+D	PS+E
NO3 (%)	0.006	0.003	0.003	0.0032	0.0047	0.042	0.0042
PO4 (%)	0.005	0.002	0.003	0.0038	0.0045	0.0042	0.0033
K (%)	0.085	0.035	0.038	0.039	0.047	0.045	0.045
Ca (%)	0.025	0.01	0.12	0.14	0.19	0.19	0.19
Mg (%)	0.03	0.05	0.03	0.038	0.042	0.041	0.041
SO4 (%)	0.021	0.064	0.021	0.028	0.035	0.033	0.031
Zn (ppm)	0.2	0.48	0.2	0.22	0.30	0.32	0.33
Cu (ppm)	0.21	0.23	0.18	0.21	0.22	0.25	0.33
Pb (ppm)	0.1	0.23	0.12	0.12	0.16	0.19	0.25
Fe (ppm)	6.4	8.0	6.3	6.4	7.2	7.1	7.2
Mn (ppm)	0.9	1.25	0.87	0.89	0.92	1.02	1.02

PS=Pure Soil FA = Flyash.

A = 10% B=20% C=30% D=40% E=50%.

Table 4. Mineral phases detected by x- ray diffractometer.

PHASES	SS	CS	FA
Quartz (SiO ₂)	Present	Present	Present.
Albite K(AlSi ₃ O ₈)	Present	Present	Present.
Augite (CaMgFeSi ₂ O ₆)	Present	Present	Absent.
Mizzonite (NaKCa(SiAl)O ₁₂ Cl)	Present	Absent	Absent.
Lazulite(MgFe)(Al ₂)(PO ₄) ₂ (OH) ₂	Present	Absent	Absent.
Metaluminite (Al ₂ SO ₄) (OH) ₄ 5H ₂ O	Present	Absent	Absent.
Hematite (Fe ₂ O ₃)	absent	Absent	Present.
Mullite (Al ₆ Si ₂ O ₁₃)	absent	Absent	Present.
Esperite (CaPb)ZnSiO ₄	Absent	Absent	Present.
Nepoutite (NiMg) ₃ Si ₂ O ₅ (OH) ₄	Absent	Absent	Present.
Tenorite (CuO)	Absent	Absent	Present.
Anthorite (CaA ₁₂ Si ₂ O ₈)	Absent	Present	Absent.
Montmorillonite (SiO ₂ .Al ₂ O ₃ .Fe ₂ O ₃ .MgO.CaO.Na ₂ O)	Absent	Present	Absent.

SS = Sandy Soil; CS = Clay Soil; FA = Fly ash.

Table 5. Available plant nutrient in sandy soil and flyash amended soil.

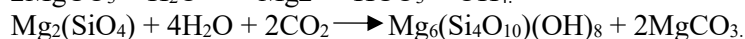
Element (%)	PS	FA	PS+A	PS+B	PS+C	PS+D	PS+E
NO3 (%)	0.002	0.003	0.002	0.003	0.0025	0.0025	0.0026
PO4 (%)	0.004	0.002	0.003	0.0037	0.0037	0.0037	0.0032
K (%)	0.45	0.035	0.031	0.04	0.039	0.039	0.038
Ca (%)	0.19	0.1	0.09	0.12	0.12	0.13	0.13
Mg (%)	0.15	0.003	0.018	0.022	0.02	0.02	0.021

SO4 (%)	0.012	0.05	0.02	0.035	0.03	0.03	0.029
Zn (ppm)	0.5	0.48	0.31	0.38	0.38	0.4	0.42
Cu (ppm)	0.18	0.23	0.19	0.2	0.21	0.21	0.2
Pb (ppm)	0.9	0.23	0.09	0.12	0.15	0.15	0.18
Fe (ppm)	5.0	8.0	5.7	6.2	6.2	6.5	6.5
Mn (ppm)	0.85	1.25	0.8	0.95	0.95	1.02	1.02

PS = Pure Soil FA = Fly ash.

A = 10% B=20% C=30% D=40% E=50%.

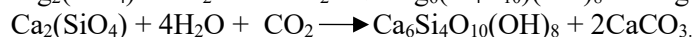
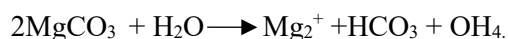
Ca and Mg in soil and fly ash are in the form of silicates and oxides. Like primary nutrients, the secondary nutrients (Ca, Mg, and SO₄) also play a significant role in the formation of plant tissue. An initial increase at the lower level was attributed due to the combined contribution of various factors discussed earlier. The possible chemical transformation for the release of Ca and Mg is discussed below [15].



Sulphur is taken up by plants in SO₄²⁻ form. It is reported that some bacteria *Thiobacillus ferrooxidans* is responsible for the oxidation of inorganic sulphur to sulphate [16]. The decrease in the macronutrients (primary and secondary) at a higher level of fly ash may be attributed due to the combined effect of imbalanced clay, silt, and sand content, microbial activity, organic matter, and pH. Some researchers have reported that high concentrations of fly ash increase the activity of a few heavy metals and interfere with microbial action [17]. PH plays an important task in the release of certain nutrients. The availability of nutrients is maximum when pH is between 6.5 to 7.5; the precipitation potential of various metals differed with respect to pH. At higher concentrations, heavy metals such as Mo and B turn into more active and form inorganic complexes that reduce the release of necessary nutrients such as N, P, and K [18].

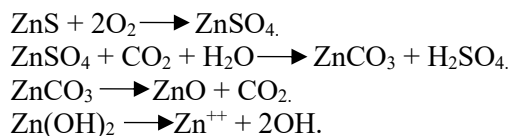
Micronutrients

Excess of heavy metal may lead to phytotoxicity in the plants. This is more likely in acidic media, sandy soils, or plants with low tolerance to heavy metals. Most heavy metals play an important role in plant physiology. In soil, Fe and Mn have an oxidative or catalytic effect and maintain any nutrient balance for regular growth. Plants assimilate iron in ferrous form. The formation of Fe⁺⁺ (soluble) and Fe⁺⁺⁺ (insoluble) depends on the redox potential of cell sap. It indicates that the availability of Fe is more than Mn. It is reported if Fe concentration is more than Mn, then Fe deficiency was not observed. The results show that Fe and Mn availability increased with increasing fly ash concentration, whereas Fe was not toxic to plants. In this case, Mn oxidizes Fe⁺⁺ (soluble) to Fe⁺⁺⁺ (insoluble) first. This reduced the availability of soluble Fe that could cause toxicity. Second, the reaction that occurs between carbonate ions and iron reduces the availability of excess iron to the plant. The chemical interactions undergoing are cited below:



Insufficiency of Mn might cause chlorosis in plants as it acts as a catalyst for oxidation-reduction with iron and nitrogen metabolism. Mn deficiency has been induced in plants if large amounts of Zn and Cu are present. Zn and Cu are higher in bottom fly ash mixtures, although no such symptoms have been observed so far. This is probably due to the physicochemical properties of fly ash that modified

the soil to silt loam when mixed with fly ash and the presence of Ca and Mg oxides that retain alkalinity. In fly ash, Zn is present in the form of esperite. The different chemical reaction undergoing to release Zn is stated as:



Cu is a necessary oxidase. It functions as an “electron carrier” for enzymes that cause redox and regulate plant respiration [19]. Cu has been reported to help accumulate Ca and Mg. In fly ash, it is in the form of tenorite (CuO). It interacts with inorganic acids released during hydrolysis of various compounds and helps release available Cu. The possible reaction taking place for the release of available Cu is as cited below:

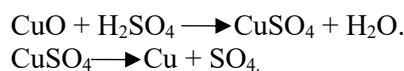


Table 2A shows that Cu increased with increasing fly ash concentration, but was not toxic because excess availability was hampered by alkaline pH, organic matter, and clay content. Lead undergoes the same mechanism as that of Cu. The apprehension of toxicity due to Pb is meager as it is available in the insoluble form.

Extensive research in the same area is required, which would certainly help to explore the problem of toxicity which could be imparted due to the presence of some heavy metals in fly ash. Long-term study is under progress.

CONCLUSION

The results of the present study demonstrate that fly ash application can help modify different soil types. The clayey soil after mixing fly ash overcame the problem of waterlogging due to increased infiltration rate and reduced cracking due to lower toughness. Therefore, it can be concluded from the present studies that fly ash acts as an improver and secondary fertilizer source. Fly ash can be an environmental pollutant, but when used properly, it can benefit the agricultural sector and provide a safe disposal solution.

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