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Utilization of Fly Ash in Agriculture: Perspectives and Challenges

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Abstract: In recent decades, significant attention has been directed towards developing strategies for fly ash utilization, with a particular emphasis on its application in agriculture. Using fly ash as a soil amendment is viewed as a financially viable choice. This is due to its distinct physical attributes, including texture, water retention capacity, bulk density, and pH, as well as its rich nutrient content, making it a promising material for agricultural purposes. It can be utilized in soils where synthetic fertilizers or organic compost show limited effectiveness, either independently or in conjunction with them, to achieve additional benefits such as enhancing soil structure and increasing crop yield. The quantity and method of fly ash application vary based on factors such as soil type, crop variety, prevailing agro-climatic conditions, and the characteristics of the fly ash itself. Despite its potential advantages in agricultural applications, including addressing nutrient deficiencies and controlling pests, fly ash also contains various toxic heavy metals and radioactive materials. Therefore, careful attention must be paid to several crucial aspects of fly ash usage in agriculture, including its long-term impact on soil health, the absorption of heavy metals, plant physiology and growth, crop quality, and on-going soil monitoring. Moreover, the potential risks associated with heavy metal toxicity, leaching, and bioaccumulation due to excessive application of fly ash should be carefully considered

1. Introduction

The industrial world is built on electricity, and technology that propels economies around the globe depends either directly or indirectly on it. Due to improper disposal methods, billions of tonnes of fly ash and other by-products from the use of coal as the main source of electricity production since 1920 have had a severe negative environmental impact (Yousuf *et al*., 2020). Improper management of fly ash can lead to contamination of soil, water, and air. However, recent technological advancements have transformed fly ash into a valuable resource, especially in the construction industry. When pulverized coal is injected into the combustion chamber of a boiler and rapidly ignites, it produces molten mineral residue. As this debris cools after the boiler's heat are removed, it solidifies into ash. Fine ash particles are captured by particulate pollution control devices like electrostatic precipitators (ESPs) in the flue gas, while the coarser residue, known as bottom ash, settles at the bottom of the combustion chamber.

India ranks as the third-largest producer of coal-fired power globally (Garg and Kaur, 2015), following China and the United States, with a significant proportion of fly ash generated due to the low-grade and high-ash-content nature of Indian coal (30-45% compared to 10-15% in imported coal). This resulted in a total of 226.13 million tonnes (MT) of fly ash in 2019-20. The disposal of this fly ash requires extensive land, contributing to on-going atmospheric pollution. Ash ponds cover a total area of 65000 acres in India (Haldive and Kambedkar, 2013). According to a study by India's Central Electricity Authority (CEA), power plants burned 678.68 MT of coal in 2019-2020, generating an average of 210 MT of Fly Ash (FA), which could rise to 437 MT by 2030 (Central Electricity Authority, 2020a; Utilisation, 2013). India consumes a lot of non-coking coal, which has a high ash content of around 30-40% (Ranjan Senapati, 2011). The produced FA from thermal power plants, on the other hand, had only 59% utilization (Central Electricity Authority, 2020). The amount of electricity produced by thermal power industries is then exploited by FA as a serious solid waste disposal issue. The inorganic debris and pavement materials are known as flue gas or Powered fuel ash (PFA), are produced by the high-temperature combustion of powdered coal as small dark flecks (Kumari, 2020). The heavy metal contamination caused by FA disposal in an unscientific manner influences local environments by degradation and leachate production (Tiwari *et al.*, 2016). Aside from taking up a lot of space, fly ash may also become airborne if it is not properly handled. The mobilization of radioactive metals in dumped FA contaminates surface and air, soils, and trees. As a result, coal-based thermal power plants face two main challenges: (1) Land requirements for fly ash disposal, and (2) Contamination, suspended particulate matter, and heavy metal transport into groundwater and the food chain (Satapathy *et al.*, 2020).

The Ministry of Environment and Forest has issued several notifications aiming to achieve 100% utilization of fly ash, thereby mitigating its environmental impact and reducing the need for land disposal (Ministry of Environment and Forests (MoEF), 2006). Since 1994, the Ministry of Science and Technology (GOI) has implemented various technologies to promote the effective and sustainable utilization of fly ash. Consequently, fly ash utilization has increased from 6.64 million tonnes in 1996-97 to 187.81 million tonnes in 2019-20 (Central Electricity Authority, 2020). FA is an amorphous combination of Ferro aluminosilicate minerals that include silica, aluminium, iron, calcium, magnesium, arsenic, chromium, lead, zinc, and other poisonous metal oxides, as well as other toxic metals. It is a heavy radioactive waste that poses significant health risks, and scientists and environmentalists have been working on its careful handling and disposal in recent years. (Latifi *et al.*, 2015) conducted a study in a variety of fields, including road building and brick manufacturing, cement, ceramics, and distempers, which are not classified as hazardous wastes. FA has been used as an alternative to another industrial resource, operation, or application for various reasons, including preventing environmental contamination, reducing disposal costs and dumping ground, replacing more expensive resources, and gaining financial returns (Ahmaruzzaman, 2010).

Various studies have also shown that FA contains important plant nutrients other than nitrogen, phosphorus, and potassium which are beneficial for agricultural applications. Researchers are investigating whether FA, which delivers nutrients to the soil, improves crop growth and yield as a bio-fertilizer and it was found that the agricultural sector uses around 0.7% - 2% of the produced FA (Kumar *et al.*, 2005). The inclusion of heavy metals in soluble form in FA has the potential for agricultural use (Pandey and Singh, 2010). However, there are certain drawbacks due to the slower rate of degradation after application in soils. For the removal of heavy metal, traditional treatments for treating FA are costly and time-consuming. Direct application of FA improves soil pH, aeration, and percolation, but a slower rate of heavy metal oxidation is a significant constraint for the agricultural environment (González and González-Chávez, 2006).

Despite its reputation as an obnoxious waste, fly ash contains vital nutrients and minerals, making it a valuable option for agricultural additives to increase plant quality and mitigate soil nutrient depletion. This article aims to address the classification and application of fly ash in agriculture, as well as the limitations that come with it.

2. Production and Utilization of Fly Ash - Indian scenario

Fly ash generation and utilization have undergone significant changes and developments from 1996 to 2020, driven by advancements in technology, regulatory requirements, and evolving perspectives on waste management and resource utilization. Currently, coal-based power generation plants generate 72% of total electricity in India, and this productivity rate with our reliance on such plants are expected to remain constant in the coming years. Fly ash production was found to be 226.13 million tonnes in 2019-20 due to the burning of 678.68 million tonnes of coal/lignite, while the fly ash consumption is around 187.81 million tonnes, implying an efficient utilization of 83.05 %. Fly ash is now widely used in the building industry, such as in the manufacture of Portland pozzolana cement, the construction of bridges, dams, slope stabilization, and so on. The official statistics (Table 1) released by the Central Electricity Authority in its annual report for 2019-20.

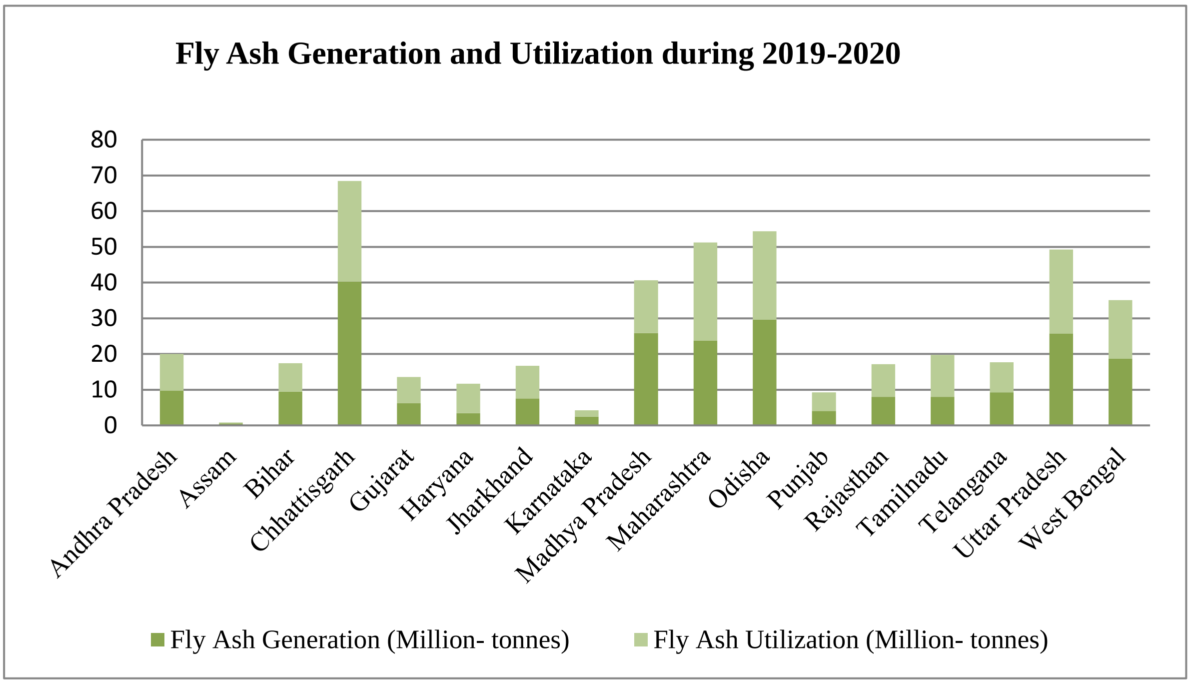

Figure 1: Graphical representation of fly ash genration and utilization during 2019-2020

Figure 1 depicts a graphical representation of the official statistics released by the Central Electricity Authority in its annual report for 2019-20. The graph illustrates that Chhattisgarh had the highest generation and utilisation of fly ash in 2019 and 2020, followed by Orissa, Maharashtra, and Madhya Pradesh.

Table 1: **The generation and utilisation of fly ash in 2019 and 2020**

Sr.No.	NameofState	Generation of Fly Ash (Million-Tonnes)	Utilization of Fly Ash (Million-tonnes)
1	Andhra Pradesh	9.6780	10.3680
2	Assam	0.5244	0.3290
3	Bihar	9.4215	8.0378
4	Chhattisgarh	40.2526	28.2042
5	Gujarat	6.2029	7.3449
6	Haryana	3.4058	8.2794
7	Jharkhand	7.5468	9.1842
8	Karnataka	2.4343	1.8272
9	Madhya Pradesh	25.8790	14.7990
10	Maharashtra	23.7703	27.4739
11	Odisha	29.6211	24.7430
12	Punjab	4.0932	5.1469
13	Rajasthan	8.0172	9.1355
14	Tamilnadu	8.0281	11.7616
15	Telangana	9.2185	8.4345
16	Uttar Pradesh	25.7889	23.4399
17	West Bengal	18.6768	16.4036
	Grand total	**232.5595**	**214.9125**

3. Fly Ash Characterization

3.1 Properties: Physical, Chemical, and Mineralogical

Typically, 65–90% of fly ash particles have a diameter smaller than 0.010 mm, giving it a silt loam appearance (Roy et al., 1981). Fly ash comprises approximately 1% of the total mass, consisting of hollow spheres known as cenospheres that are easily dispersed in the air and filled with tiny particles called plerospheres and crystals. Research indicates that fly ash has a low specific gravity ranging from 1.6 to 3.1 g/cm^3, a low bulk density of 1.01–1.43 g/cm^3, and poor hydraulic conductivity (Eary et al., 1990). Fly ash typically consists of fine particles, with sizes ranging from a few micrometres to tens of micrometres. The particle size distribution influences properties such as flowability, compaction, and surface area. Fly ash density varies depending on factors such as particle size, shape, and porosity. It generally ranges from 1.5 to 2.5 g/cm^3.Fly ash contains void spaces between particles, which affect its water absorption capacity, permeability, and compressibility. The specific surface area of fly ash is an important parameter affecting its reactivity and adsorption capacity. Finer particles generally have higher specific surface areas.

The composition of fly ash varies depending on factors such as the coal type, combustion conditions, and post-combustion treatments. It typically comprises silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and other oxide compounds. The presence of calcium oxide and other alkaline compounds often results in fly ash having an alkaline pH. Trace elements like arsenic, cadmium, chromium, lead, and mercury may be found in fly ash, influenced by the source of coal and the combustion process. Monitoring these elements is essential to evaluate environmental impacts and ensure safe utilization. Additionally, toxic elements such as 40K, 226Ra, and 232Th might also be detected (SrinivasaRao et al., 2019). The pH influences its interaction with soil, water, and other materials. The pH of fly ash ranges from 4.5 to 12.0, depending on factors like coal sulphur content and combustion techniques. Typically, fly ash waste exhibits alkaline properties with a Ca/S ratio of 2.5 (Szponder and Trybalski, 2011).

The main components of fly ash consist mainly of non-crystalline substances such as silicon-aluminium glass, accounting for approximately 80% of its composition. Additionally, it contains several crystalline phases including gypsum, mullite, quartz, magnetite, anhydrite, ettringite, opaline, hematite, lime, spinel, chlorite, and feldspar (Ahmaruzzaman, 2010). Figures 2 and 3 offer detailed insights into the nutritional content and heavy metal composition of fly ash, respectively.

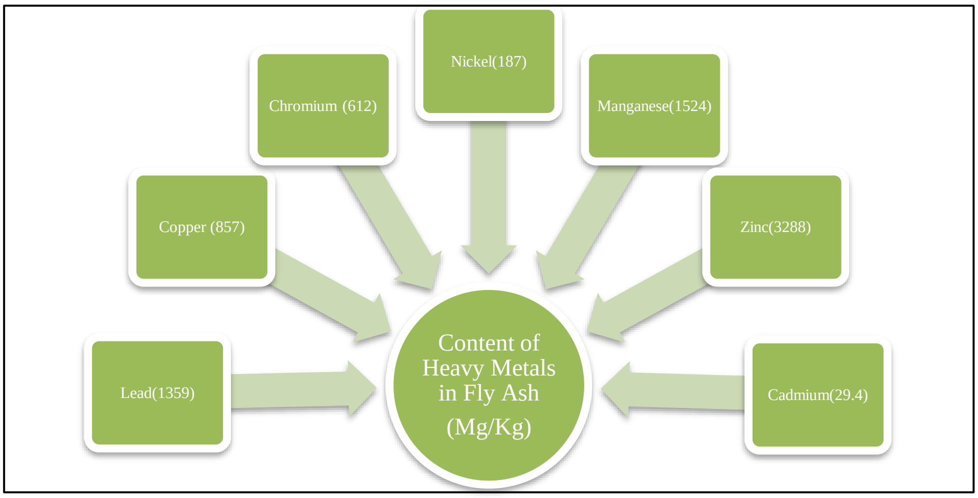

Figure 2. Content of Heavy Metals in Fly Ash

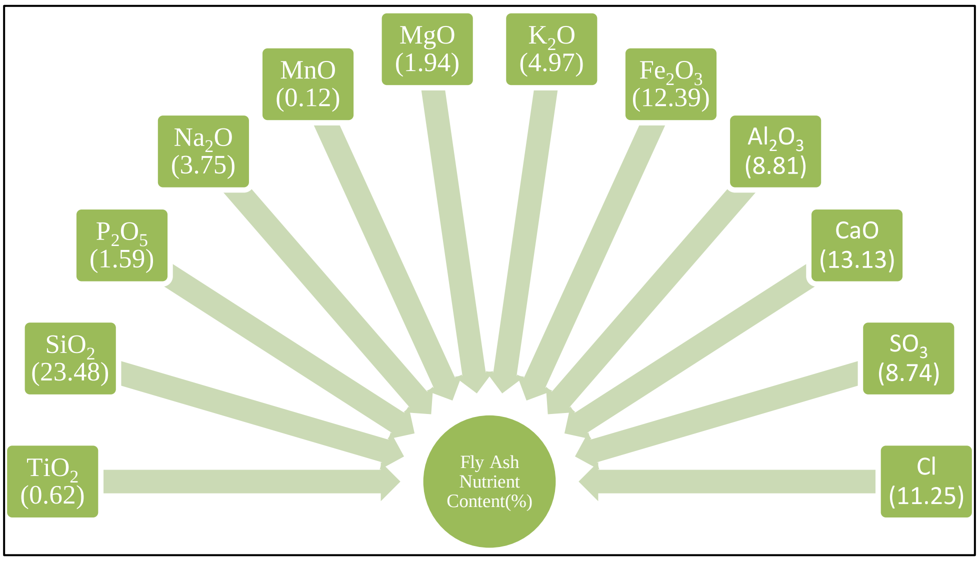

Figure 3. Nutrient content (%) in fly ash

Agricultural utilization of Fly Ash

FA can be treated as a possible fertilizer substitute for contaminated soils, alleviating some of the solid waste management issues. There is an urgent need to look after the contamination of heavy metals that are harmful to humans, soil life, and plants above their essential thresholds (Karim *et al.*, 2019). FA has potential advantages and may become a valuable agricultural input. Application of 200-400 tonnes per hectare FA to sandy loam soil results in substantial increases in moisture holding capability, permeability, total transferable bases, bulk density, and acidity, as well as improved crop yield. Addition of 10% FA to sandy soil can result in a 52% increase in plant usable water (Kumari, 2020; West and McBride, 2005). The alteration in soil pH following the application of fly ash (FA) is influenced by several factors, including the initial pH contrast between the FA and the soil, as well as the soil's buffering capacity. Incorporating FA into various ratios of soil enhances its porosity by 10%, texture, water retention capacity by 15%, rigidity, pH levels, bulk density, and other attributes. The introduction of FA into clayey soil leads to a significant reduction in water retention capacity (WHC) and bulk density. This addition also promotes enhanced nutrient mobility due to increased soil porosity and reduced runoff. Utilizing FA has been shown to increase seed and grain yields in both Kharif and Rabi crops during their respective growth periods (Dahiya and Budania, 2018). It boosts cereal, oilseed, pulse, cotton, and sugarcane yield by 10-15%, vegetables by 20-25%, and root vegetables by 30-40%. It was also found that tomato plants grew more lushly in a FA mixture, with larger, greener leaves. FA can be used as an amendment in the agriculture sector since it contains various micronutrients. It is also used as herbicides to keep the pH of agricultural soils stable and keep the land fertile. If fertilizers are also added, plant growth & crop yield can be increased when FA is combined with infertile loam soils and acidic mine spoils (Kumar and Singh, 2003). FA was found to be a healthy soil improver and a source of micronutrients. FA also increases WHC (by reducing irrigation requirements by 10-15%), texture, aeration, and crust formation. FA is also an excellent amendment for sodic and saline soils and reclaiming other contaminated or problematic soils. A single field application of FA/pond ash improved yield and soil quality for up to 7-8 years without causing any harmful effects on soil or crop produce quality due to chemical or other properties of FA (Kumar and Jha, 2014). The different applications of FA in agricultural sector are as shown in Figure. 4.

For the Australian coal ash industry, (Aiken and Heidrich ,2015) created a new national supply model to serve various agricultural enterprises and to ensure environmental safety, fixed maximum chemical concentration levels and routine monitoring intervals were used. This strategy tackles a demand shift from low-value, high-volume regional production to high-value, high-volume FA that is spread throughout the country. Establishing a fly ash (FA) supply chain to meet the demands of the Australian agricultural sector would require careful management of shipping logistics, along with comprehensive tracking and evaluation of materials and their end-use (Aiken and Heidrich, 2015). Fly ash exhibits the potential to boost soil quality and enhance crop production efficiency. The degree of soil pH adjustment resulting from fly ash application depends on factors such as the disparity in pH between the fly ash and the soil. Fly ash applications have been noted to address deficiencies in essential plant nutrients, including phosphorus (P), manganese (Mn), boron (B), magnesium (Mg), molybdenum (Mo), sulfur (S), and zinc (Zn). The impact of fly ash on microbial activity is generally inconsistent, although it tends to be beneficial at lower doses or when combined with other organic amendments. According to (Saraswat and Chaudhary, 2015), the impact of FA is reduced at higher doses, especially with high- pH ashes. Srivastava and Kumar investigated the impact of FA modification on the growth of *Sesbania cannabina*, a green manure seed (Dhaincha). The Indian Farmers Fertilizers Cooperative Limited (IFFCO) in Phulpur provided the FA used in this analysis. Plants were grown in 100% FA only lasted around two months and had slightly lower biomass. According to the report, up to a 75 % amendment level had no negative impact on *SesBania* pea plant development, hence thisplant can be employed for the reclamation of fly-ash deposited sites (Srivastava *et al.*, 2015).

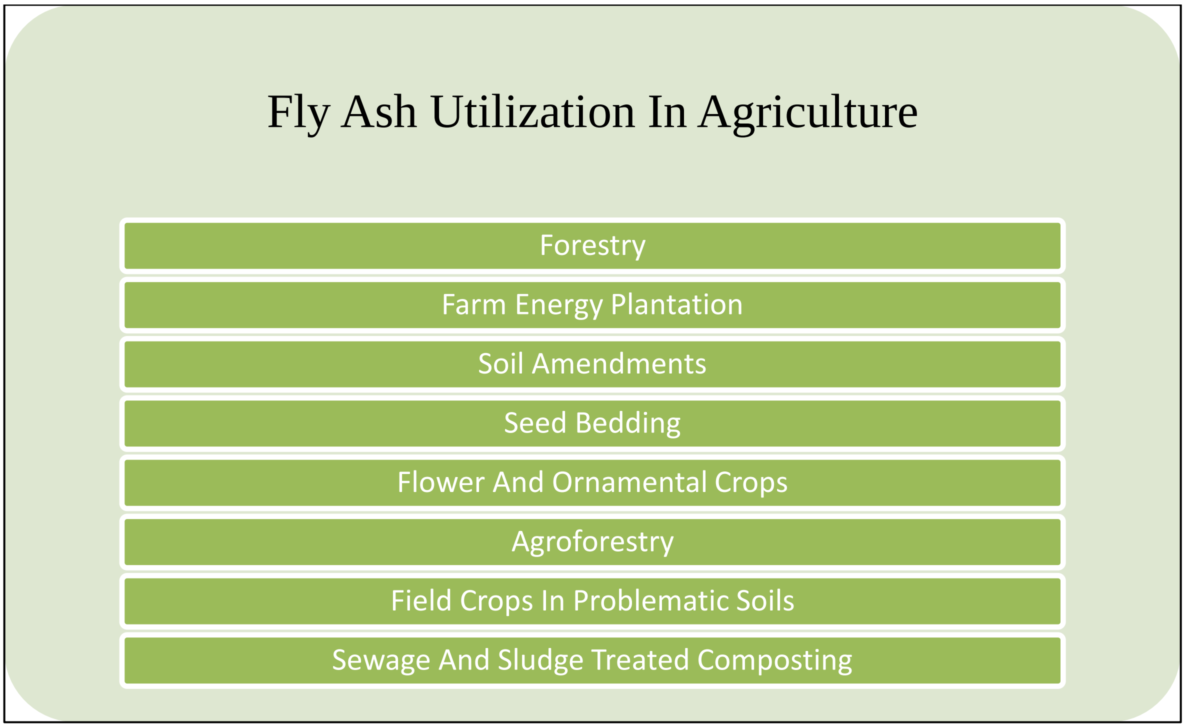

Figure. 4. Fly ash utilization in agriculture sector

(Raj and Mohan, 2014) proposed a method for improving plant growth by amending soil with FA. As used in various ratios of soil, FA increases the texture, water-holding ability, stiffness, pH, bulk density, porosity, and other properties. The application of FA to Kharif and Rabi crops improved seed grain yield during their respective growing seasons. In addition, the growth of sunflower plants treated with FA was increased. The relative growth rate and net assimilation also increased by more than 20% (Raj and Mohan, 2014). (Singh et al., 2010) investigated the physio-chemical properties of FA, three related soils, and irrigation water. Chilli plant development was analysed in soils containing 0 %, 2 %, 5 %, 10 %, 15 %, 20 %, and 25 % FA. At 10% mixing, the maximum plant height of 13.5 inches, 60number of leaves, 33 number of flowers and 23 number of fruits for S1 in winter were observed. During the wet, winter, and summer seasons, the average maximum amount of fruit was located at a mixture concentration of 5% to 10% (Thakre *et al.*, 2013). (Singh *et al.*, 2010) investigated the output of a variety of crops grown in soil amended with FA. The soil was modified with FA from the Chandrapur Thermal Power Station in Jharkhand, India. The pH of the FA sample was 7.56, while the soil pH was 6.65. In the dry state, the specific gravity was 2.21g/cm^2, while the bulk density was 1.32g/cm^2 and 1.22g/cm^2 in the wet state (Singh et al., 2010).

The impact of coal FA on agricultural crops was investigated by (Arivazhagan et al., 2011). The four separate amendments tested had no negative impact on Sesbania pea plant growth up to a level of 75%. It was also recommended to use FA in the reclamation of FA deposited sites to aid in the management of land use and food security issues. The report proposes a more efficient use of thermal power plant waste in bulk and solutions to food protection and land-use problems. Before the Kharif/rabi season, the researchers researched the thermal power station areas to persuade farmers to use ash in their fields (Arivazhagan *et al.*, 2011). (Dasgupta and Paul, 2011) investigated FA and its effects on land to determine the main characteristics of the research area's land-use trend. With the expansion of cities, the forest cover has also decreased to 10%. Paddy cultivation now occupies a portion of the land formerly used for flower cultivation. Over the last three decades, the amount of farmland has risen by around 5%. The finding shows the extent to which FA affects flower cultivation (Dasgupta and Paul, 2011).

The usage of FA in agriculture to enhance soil fertility and its productivity was investigated by (Kishor *et al.*, 2010) and the fertilizers or soil additives have been identified after repeated field trials to validate their consistency and protection for each type of soil.

Soil amended with fly ash (FA) improves soil structure, reduces bulk density, enhances water-holding capacity, optimizes pH levels, and boosts soil buffering capacity. A can also be used as an insecticide which reduces the mobility and availability of metals. However, because of the high pH (generally in between 8 and 12), high salinity, and high concentration of phytotoxic elements, particularly boron, some nutrients are less bioavailable (Kishor *et al.*, 2010). (Aggarwal *et al.*, 2009) detected the use of FA in grain production and its effect on wheat and sorghum crop growth and soil properties. The physical and chemical characteristics of soils from both testing sites and FA used in the research were investigated. Increased amounts of FA and nitrogen had a direct impact on sorghum growth characteristics. With 40 kg N + 20 tonnes per hectare of FA, the maximum average plant heights of 162 cm were reported. Grain and biomass yields improved steadily with the addition of FA and nitrogen levels, which were 11.8 % and 14.3 % higher with 20 tonnes per hectare FA than with control. The harvest index of Sorghum improved as N and FA levels increased, which was found between 21.6 to 29.0 %, with a mean value of 24.95 % (Aggarwal *et al.*, 2009).

(Yeledhalli *et al.*, 2008) conducted long-term field studies to investigate the bulk application of fly ash (FA) or pond ash at rates of 30-40 tonnes per hectare, either as a one-time application or as repeat applications. The study evaluated the effectiveness of using only NPK fertilizers or a combination of farmyard manure at a rate of 20 tonnes per hectare for cultivating sunflower, corn, and other crops in irrigated vertosols in rotation. The application of FA had a major impact on mechanical composition. Due to the application of FA, soil porosity rose slightly from 50.9 % to 51.7 % and it was observed that the WHC of the soil rose dramatically. The pH, Electrical Conductivity and bulk density of soil did not change appreciably by the addition of either FA or pond ash. Sand content rose from 9.2% to 10% and that of silt increased from 27.0% to 28.5%. The soil clay content dropped from 63.8 to 61.6% (Yeledhalli *et al.*, 2008). (Mittra *et al.*, 2005) developed an advanced plant nutrient supply scheme for rice–peanut cropping systems using FA and other agricultural waste such as sludge from paper factory, residue from farmyard manure crop, and chemical fertilizer. Rice seedlings grown in nursery bed for 45 days were used to move rice in puddle soil. FA was added at a rate of 10 tonnes per hectare, and organic content such as farmyard manure was applied in sufficient quantities to include

30kg of nitrogen per hectare and 2 tonnes of lime per hectare. The use of organic content in conjunction with chemical fertilizer improved soil fertility by increasing the soil's nutrient-supplying capability.

The combined application of farmyard manure and chemical fertiliser boosted the absorption of nutrients such as Ca, Mg, Mn, Zn, Cu, and Co when compared to when the fertiliser was applied alone or in combination with organic sources. Utilising fly ash or lime as an amendment, fertiliser, and farmyard manure as an organic source improved the quality, production, and nutrient uptake of rice dry matter.

Estimates indicate that it would provide about 27 kg of organic carbon in addition to significant amounts of other vital nutrients including potassium (25 kg), zinc (238 mg), copper (238 mg), manganese (2.8 kg), iron (127 kg), calcium (33 kg), magnesium (17 kg), and manganese (238 mg). Therefore, adding FA in the right amount to any organic content produces a whole blend of nutrients and organic carbon that is required to increase crop output (Mittra et al., 2005).

4. Role of FA in agriculture diseases control

FA has been reported to be effective as an insecticide in rural fields by (Sankari and Narayanaswamy, 2007). Lignite fly ash (FA) has insecticidal qualities that can destroy a variety of lepidopterous as well as coleopterous insects that are frequently found in vegetables, rice, greens and other field crops, according to Basu et al. (2009). The effectiveness of herbal pesticides made from fly ash against pests that damage rice and vegetables was examined by (Sankari and Narayanasamy, 2007). They found that the combinations of fly ash with 10% turmeric dust, as well as fly ash with 10% neem seed kernel dust, worked best against all of the insects they tested, including Epilachna on brinjal and Spodoptera on okra.These mixtures were succeeded by fly ash mixed with 10% vitex, fly ash mixed with 10% eucalyptus, and fly ash mixed with 10% osmium. According to (Singh *et al.*, 2010), fly ash may be used in pesticide formulations including soil, wettable powder, and granules as both an insecticide and an active carrier.

The effects of applying lignite fly ash (LFA) dust topically on the papaya leaf curl viral disease and the Bemisiatabaci population that carries it were studied by Eswaran and (Manivannan ,2007). After planting, they gave the plants varied amounts of LFA at different times.Papaya leaf curl virus disease and its vector were successfully managed by foliar applying LFA dust at a rate of 2 kg per plant at 90 and 120 days following planting, according to Eswaran and (Manivannan's ,2007) observations.

Applying LFA twice, specifically at 90 and 120 days after planting, yielded better results compared to applying it once at multiple intervals (30, 60, 90, and 120 days after planting). The fly ash remained on the leaf's surface for nine to twelve days.

It has been verified that further lignite FA application will reduce the vector population and produce a papaya harvest free of disease. Additionally, the use of LFA dusts greatly enhanced plant resistance mechanisms, which in turn raised fruit yield (Eswaran and Manivannan, 2007). Furthermore, a number of studies have found that FA is a successful way to manage a range of pests that infest different types of vegetables, both in laboratory and field settings.

5. Recommendations and viewpoints

Fly ash, a by-product of coal combustion, can indeed be utilized to improve soil conditions, especially in degraded soils. Combining fly ash with biological waste such as animal manure or sewage sludge can enhance its effectiveness as a soil amendment. This mixture can help promote the growth of commercially valuable plants and facilitate agricultural regeneration, particularly in industrial areas where soil quality may be compromised (Sahu et al., 2017).

However, it's crucial to conduct thorough analysis to understand the long-term impacts of fly ash on soil sustainability, fertility, and overall quality. Monitoring of both the soil and fly ash properties over time is essential to ensure that the intended benefits are realized without causing any adverse effects on the environment or human health. The study by (Sahu et al. ,2017) likely provides valuable insights into the application of fly ash as a soil conditioner and the importance of on-going monitoring to assess its effectiveness and potential risks.

6. Conclusion

Fly ash (FA) should be regarded as a valuable resource rather than as waste. Its potential as a resource material in manufacturing, agriculture, and other related industries has garnered significant recognition in recent decades.To make the best use of FA, significant action must be taken both domestically and internationally.

Two of the most significant attributes that make fly ash (FA) suitable for agricultural applications are its texture and its comprehensive nutrient composition, encompassing nearly all essential plant nutrients, except for organic carbon (C) and nitrogen (N). FA can be used in conjunction with chemical fertilisers or organic manure to enhance soil properties and yields, among other benefits. However, it cannot completely replace these methods of soil modification. Depending on the kind of soil, the crop being grown, the agroclimatic conditions at the time and the qualities of the FA, there will be differences in the amount and technique of applying FA to the soil. Various advantages of FA an input material for agricultural applications is known, however, precautions need to be taken so that the concentration of trace/toxic metals does not increase beyond the threshold values. Since, excess application of FA in the agricultural field may lead to the bioaccumulation of these trace/toxic metals in the soil biota and my result in leaching problems. Thus, extreme caution must be used when applying FA in agriculture. Long-term studies of the impact of FA on crop quality and soil health, as well as on going soil and FA characteristic monitoring, should be given top priority. Since there aren't many studies in this area, further research is required to determine what happens to radionuclides contained in FA after they are used for an extended period of time in agriculture.

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