Article

Reclaiming oligotrophic agricultural land using FA as a soil conditioner: Integrating organic and inorganic materials to improve soil ecosystem for better crop productivity

Anjali Verma, **Chandralekha Piparia**, **Santosh Kumar Prajapati**
Department of Botany, School of Studies of Life Science, Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh, India-495009
Email: sntshprjpt@gmail.com

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Abstract
FA (FA), a byproduct of coal combustion, is produced in large quantities globally and poses significant environmental challenges. FA also has potential as a soil amendment in agriculture due to its nutrient content and ability to improve soil properties. Despite the establishment of guidelines for FA use in agriculture by regulatory bodies, its utilization in this sector remains limited. The presence of harmful substances and application challenges are among the negative aspects of FA that require further research and development. The combustion technique influences the properties and potential uses of FA, with pulverized coal combustion (PCC) producing more consistent FA compared to fluidized bed combustion (FBC) technology. Reclamation and revegetation of FA disposal sites are crucial for converting these areas into environmentally viable landscapes. However, the unique characteristics of FA, such as high pH, limited water-holding capacity, and potential heavy metal content, make the restoration process challenging. Strategies for effective reclamation and revegetation include soil amendment, plant introduction, and ongoing monitoring. The use of organic amendments, integrated organic/biotechnological approaches, and phytoremediation with metal-accumulating plants have shown promise in improving substrate properties and stabilizing heavy metals. Native plants play a vital role in the eco-restoration of FA deposits due to their adaptability to harsh conditions. Plant-based reclamation and revegetation of FA disposal sites offer a practical solution to address environmental concerns and enhance the ecological value of these areas.

Keywords reclamation; FA; soil mulcher; sustainable agriculture; oligotrophic.

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1 Introduction

Currently, a significant amount of FA, which is a byproduct of coal burning, is regarded as a problematic solid waste globally (Varshney et al., 2022). It is an excellent soil supplement for plant growth and development because it contains both macro and micronutrients (Ahmad et al., 2021). FA increases the soil WHC, electrical conductivity, optimized pH and Porosity Microbial activity (Varshney et al., 2022). During the 1st half of 2022-2023 five states, Chhattisgarh, Madhya Pradesh, Maharashtra, Uttar Pradesh and West Bengal, each produced over 10 million tons of FA. In Chhattisgarh, the total number of thermal power plants is 23 and FA generation is 20.6330 million tons. The Intergovernmental Panel on Climate Change (IPCC) claims that the application of lime to agriculture causes global warming by releasing CO_2 into the atmosphere. In recent years, there has been an increased interest in the use of FA in agriculture to improve soil quality. The use of FA in the agriculture sector is limited. Guidelines for using FA as a soil modification and ameliorant in agriculture have been established by the CPCB and the (MoEFCC). According to a report by the MoEFCC and CPCB IIT Roorkee, FA can be used as a soil conditioner in agriculture. However, only 1.02% of the FA is currently used in this category (Fig. 1). The Ministry of Agriculture may want to encourage the use of FA as a soil conditioner in agriculture. Different types of organic and inorganic materials are added to FA and their ameliorative effects differ in terms of crop and soil physiology. while FA offers several advantages in improving soil properties for agriculture and enhancing the properties of construction materials, its negative aspects, such as the presence of harmful substances and the challenges in its application, cannot be overlooked. A byproduct of burning coal, FA is produced in vast amounts worldwide and presents serious environmental problems. Many nations are working to boost their FA utilization rates since the use of FA has grown to be a crucial concern. Average FA consumption rate is 70%, mostly for construction materials (Jin et al., 2021). Due to a lack of options outside of the construction industry, FA utilization rates are still low globally (Dindi et al., 2018). FA has relatively limited application in agriculture, as seen in Fig.1. The qualities and possibilities for using FA are influenced by the combustion technique. Although FA from pulverized coal combustion (PCC) is more constant, FA quality from fluidized bed combustion (FBC) technology, which can use low-grade fuel combinations, is more unpredictable (Ohenoja et al., 2020). This fluctuation creates possibilities as well as difficulties for the use of FA.

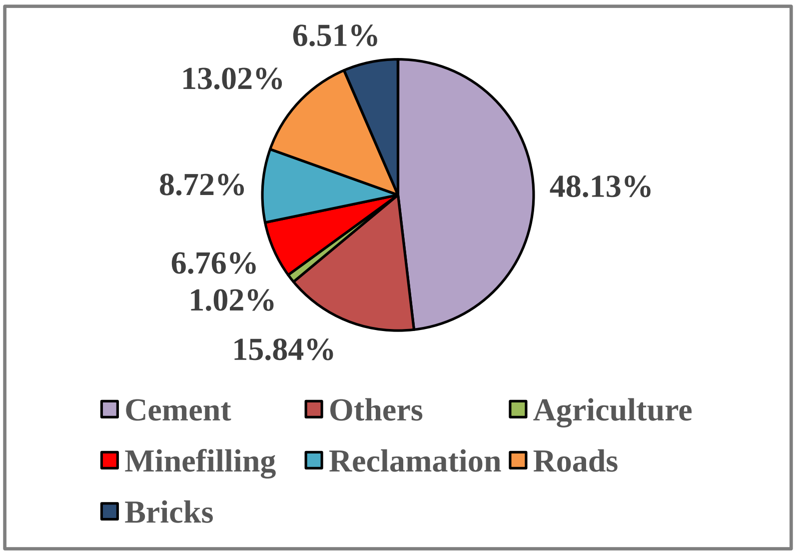

Fig. 1 Use of FA in the first half of 2022-23 (According to CSE Report).

2 FA Dykes Reclamation and Re-vegetation

The conversion of arid wastelands into environmentally viable landscapes depends on the reclamation and revegetation of FA disposal sites. Soil amendment, plant introduction, and ongoing monitoring can restore degraded regions. The special characteristics of FA and its impact on soil and plant growth make restoring and regenerating FA disposal sites difficult. FA high pH, WHC and possible heavy metal content may all make it challenging for plants to establish and grow. Because FA disposal sites provide serious health and environmental hazards, efficient reclamation and revegetation techniques are required. The greatest way to mitigate these problems is to revegetate FA disposal sites (Kostic et al., 2018). However, FA toxicity and unfavourable properties, such as its poor cation exchange capacity, high electrical conductivity, alkaline pH, and low nutritional content, hinder plant life and growth (Weber et al., 2015; Kostic et al., 2018). On FA disposal sites, soil formation has been demonstrated to be initiated by weathering and revegetation processes. These activities eventually result in improved chemical and physical characteristics, including higher nutrient content and cation exchange capacity, decreased salinity and alkalinity, and increased clay and silt fractions (Kostic et al., 2018). Water retention and plant development conditions can be improved by adding organic amendments such as boulder clay or biosolids, which can further improve substrate qualities (Weber et al., 2015).It has been suggested to use an integrated organic/biotechnological strategy that includes the utilization of legumes for nitrogen fixation, mycorrhizal inoculation, and the incorporation of organic materials (Haynes, 2009).(Fig.2)Shows several strategies for the effective reclamation and revegetation of FA disposal sites. Utilizing plants like *Ricinus communis L.* that have a high potential for metal accumulation, phytoremediation has demonstrated promise in stabilizing heavy metals and yielding financial gains (Pandey, 2013). Plant-based reclamation and revegetation of FA disposal sites is a practical way to solve environmental issues and enhance site conditions. Numerous studies have shown that various kinds of plants can be used for this.

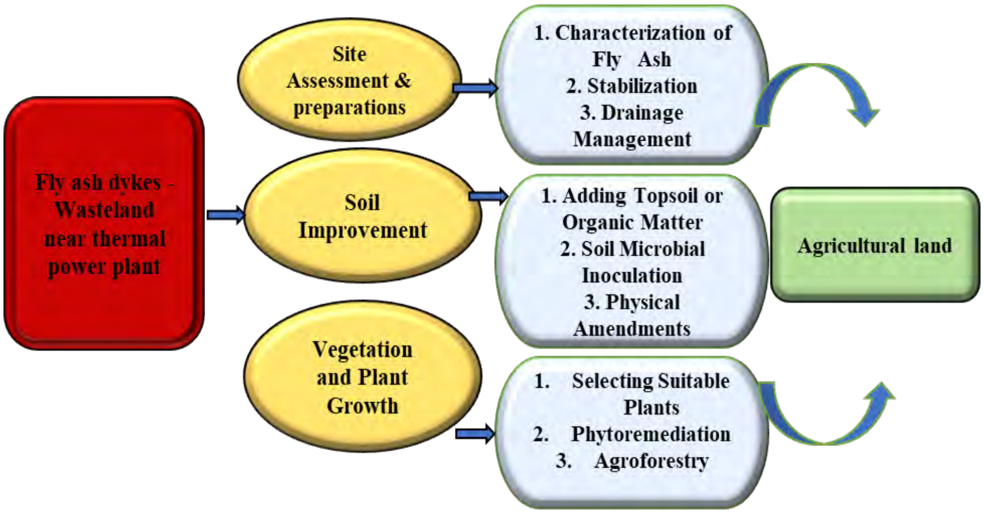

Fig. 2 Various methods for transforming FA dykes into productive agricultural land.

3 FA Mixed with Organic And Inorganic Mulcher

The burning of coal produces FA, which has demonstrated promise as a soil amendment when combined with organic matter to improve farming methods. Adding FA to organic materials has been shown to enhance crop yield and soil quality (Malik et al., 2009). According to Bhattacharya and Chattopadhyay (2002), vermicomposting FA with organic waste, such as cow dung, has been shown to boost the concentration of phosphate-solubilising bacteria, which in turn improves the bioavailability of minerals, especially phosphorus. It was discovered that the ideal FA to cow dung ratio for vermicomposting was 1:1, which led to noticeably more phosphorus availability than other treatments (Bhattacharya et al., 2002). There is potential for enhancing soil quality and crop yields by combining FA with organic matter. Research has shown that adding biochar to FA improves soil nutrients, biological characteristics, and crop yields (Masto et al., 2013). To guarantee FA is a safe and efficient application in farming methods, however, much thought must be paid to its composition and source. FA combined with inorganic matter can improve farming methods by supplying vital nutrients, but its use needs to be carefully considered. The hazards of contaminating the soil and water must be balanced against the possible advantages. To use FA in agriculture safely and effectively while reducing environmental effects, more research is required. (Fig. 3) shows the uses and advantages of FA for improving soil. FA is composed of two parts: inorganic and organic materials. FA organic matter stimulates microbial activity, decreases soil compaction, improves soil aeration and water retention, and boosts nutrient availability. The inorganic matter, on the other hand, neutralises soil pH, lowers metal toxicity, and improves soil fertility.

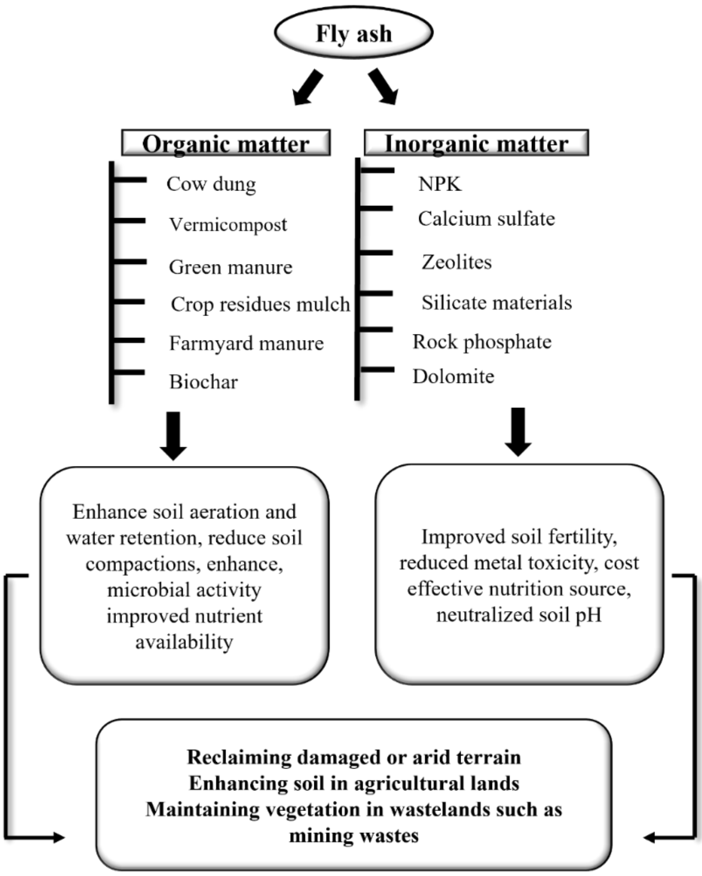

Fig. 3 Benefits Of Using FA Along With Inorganic And Organic Mulcher.

3.1 Strategies for safe and effective use of FA in agriculture

In Agriculture FA is used as a soil ameliorative agent. FA is a low-cost soil conditioner material that has many agricultural properties. They altered the soil's physical, chemical and biological properties and enhanced agricultural productivity. and increases different soil parameters such as WHC, Moisture, pH, Electrical conductivity, Aeration and Salinity (Ukwattage et al., 2013). The safe utilization of FA (Table 1) in combination with various organic and inorganic materials to enhance soil quality and plant growth. Combining FA with cow dung at dosages of 0, 50, 100, and 150 t ha^{-1}, along with cow dung at 10, 20, and 30 t ha^{-1}, significantly impacted growth parameters such as plant height, number of leaves, root length, and dry weight in *Ipomoea aquatica*. Greater plant growth was observed with 0 and 50 t ha^{-1} FA, while higher doses reduced growth, as reported by (Priyadi et al., 2023). Similarly, a combination of FA (10–100 t ha^{-1}) with NF and BGA promoted growth in *Oryza sativa L.*, improving root biomass and other parameters, with FA10 + NF90 + BGA12.5 proving optimal (Tripathi et al., 2008). Development and xylem integrity in *Typha latifolia*, with a 25% FA mixture being the most effective (Sarkar et al., 2017). Similarly, vermicompost and fertilizers with FA (10–50 tha^{-1}) significantly enhanced growth in *Cicer aritinum L.*, with the best results observed at 20 t ha^{-1} FA, which increased phosphate-solubilizing and nitrogen-fixing bacteria populations (Tripathi et al., 2020).In experiments with *Glycine max L.*, FA at 20% improved shoot and root length, leaf number, and chlorophyll content, though concentrations above this threshold led to toxicity and decreased yields (Bashir et al., 2017). FA doses of 25 g/m² with soil increased productivity and germination in *Vigna unguiculata L.*, while higher doses reduced growth (Kumar et al., 2021). Similarly, a 5–10% FA concentration improved growth parameters in *Capsicum annuum* (Thakare et al., 2013). For *Tectona grandis L.*, combining *mycorrhiza* with 3% FA enhanced root colonization, shoot and root weight, and other growth parameters (Hosmani et al., 2023). Lastly, a mixture of FA with garden soil (FA 40% + GS 60%) proved beneficial for *Calendula officinalis* and significantly improved plant growth, total phenolics, and flavonoids (Varshney et al., 2021). These studies demonstrate that FA when applied in optimized doses, can significantly enhance soil quality and agricultural productivity. However, higher dosages often exhibit toxic effects, emphasizing the need for precise application to achieve sustainable results.

Table 1 Application of FA along with an appropriate amendment to crops that grow on pot or FA dumpsite.

Combination	Dosages/ Ratio	Plant Species	Parameters Studied	Impact on growth parameter	Maximum yield at dosage	References
FA Cow dung	FA- 0, 50, 100, 150 t ha^{-1} Cow dung- 10, 20, 30 t ha^{-1}	Water spinach *(Ipomoea aquatica)*	Plant height, No. of leaves, Fresh weight of plant, Root length, Root dry weight.	The parameters of plant height, root length, and dry weight showed greater in the treatment of doses of 0t/ha and 50 t/ha. .	Water spinach grows less as FA is treated in greater amounts; they grow on 0t/ha and 50t/ha, and applying FA at doses of 100t/ha to 150t/ha decreases the growth rate.	Priyadi et al. (2023)
FA + NF + BGA	FA10, FA100(t ha^{-1}) NF90, NF120, BGA12.5	*(Oryza sativa L.)*	Photosynthetic pigments, Carotenoid, Root biomass, Plant height, No. of tillers grain, strawweight.	The development of the plants was greatly accelerated by adding NF and BGA to GS. No significant alteration in the amount of pigments and protein and increased cysteine.	FA10 + NF90 + BGA12.5 Using FA at a lower dose seems to help rice plants grow coupled with the recommended dosage of BGA.	Tripathi et al. (2008)
SOIL + FA	FA - (0%, 25%, 50%, 75%) Soil - (100%, 75%, 50%, 25%)	*Typha latifolia*	Heavy metal analysis of soil, Plant growth and xylem integrity.	Xylem structure of *T. latifolia* cultivated without FA showed considerably thinner wall integrity than the 25%growth and	Implementation of 25%, according to electron microscope observation FA was shown to improve soil N, P, Kand Si availability while	Sarkar et al. (2017)

				increases shoot length as well as plant health.	also promoting improved plant development and xylem integrity.	
Vermicompost + Fertilizers ((NPK) + FA	Vermicompost- 2 t ha^{-1} NPK- 20 KgN + 50KgNP_2O_5 t ha^{-1} FA- 10 t ha^{-1}, 20 t ha^{-1} 30 t ha^{-1} 40 t ha^{-1} 50 t ha^{-1}	*Cicer aritinum (L.)*	No. of branches, Plant height, Root nodules/plant, Dry matter weight, No. of pods/plants, No. of seeds/plants, Seed index.	All growth parameter is increased at lower FA. Phosphate solubilizing bacteria and N2 fixing bacteria are increased.	20t ha^{-1} FA - Phosphate solubilizing bacteria and N2 fixing bacteria was maximum. 50t ha^{-1} FA- significant reduction in the microbial population Higher doses of FA increase toxicity, which leads to decreased microbial populations.	Tripathi et al. (2020)
FA + SOIL	10%, 15%, 20% 25%, 30%	*Glycine max (L.)*	Shoot length, Root length, No. of leaves, Wet biomass and dry biomass of roots. Biochemical assay root and shoot in different developmental stages.	Plant height increases by 20% FA and decreases by 25 % to 30%, Root length raised-30% FA, Leaf number enhanced -30% FA, Yielding seeds -20% FA, Photosynthetic pigments Chl a, Chl *b*, increases. But declined increased concentration above 20%.	From the vegetative through the pre-flowering stage, experimental analysis reveals a significant increase in plant biomass, yield and physiological response up to a level of 20% FA. A decrease in the post-flowering stage.	Bashir et al. (2017)
FA + SOIL	FA- 25 g/m^2 50 g/m^2 100 g/m^2 0 g/m^2	*Vigna unguiculata (L.)*	Germination, Biomass, Plant length, Nodulation, Productivity and Biochemical analysis.	Increased plant productivity and germination. Higher doses of FA inhibit productivity.	25 g/m^2 FA is best for plant growth and yield.	Kumar et al. (2021)
FA + SOIL	0%, 2%, 5%, 10%, 15%, 20%, 25%	*Capsicum annuum*	No. of fruit, Plant height, No. of leaves, No. of fruit.	Increased plant growth parameter.	5-10% FA concentration is beneficial for plant growth.	Thakare et al. (2013)
FA+ Mycorrhiza	MR + 1% FA MR + 3% FA MR + 5% FA	*Tectona grandis L.*	Root and Shoot length, Stem diameter, no. of leaves, Colonization of root, fresh and dry weight of shoot and root.	Increased number of mycorrhiza spores and colonization.	MR + 3% of FA is beneficial for plant growth	Hosmani et al. (2023)
FA + SOIL	100% GS 80% GS + 20% FA 60% GS + 40% FA 40% GS + 60% FA 20% GS + 80% FA 100% FA	*Calendula officinalis*	Plant growth Total phenolics Total flavonoids.	Increased plant and other beneficial biochemicals.	Under 60% GS + 40% FA	Varshney et al. (2021)

3.2 Utilization of FA in pest control, disease prevention, and soil enhancement

According to India Agronet Insecticides FA also act as Pests controllers mostly lignite FA uses as pest controllers and protects against chewing and sucking pest FA formulation applied on Rice, Brinjal, Bhindi).

Herbal insecticides derived from FA+ *Azadirachta indica*,FA + *Vitex agnus*castus, FA+ *Eucalyptus tereticornis*, FA+ *Millettia pinnata*. Also, FA used as a weedicide on rice and other crops are beneficial for as and significantly reduces species of sedges (*Cyperaceae*) (Jawahar et al., 2010). FA also useful for disease prevention. Root-knot nematodes infect thetubers of plants and produce small warty symptoms in infected areas FA prevents *Meloidogyne* species of nematodes in Lady’s Finger plant (Bhat et al., 2023). Different types of termites like housefly maggots their mortality rate decrease in different doses of FA (Lignite) mixed with soil (Hariprasad et al., 2020). Also, FA enhanced beneficial fungus growth 3% FA and arbuscular mycorrhiza are enhanced growth of teak plant . FA is used in agriculture as fertilizers and coating materials it may be combined with various organic and inorganic elements to have a diverse effect on plant includes changes in plant biomass, plant height, dry weight and grain production (Hermawan et al. 2023). The potential for using coal FA and Azolla as coating materials in slow-release fertilizers is good for crops. FA application in a combination of FA and mining soil in the different ratios are shown different biological responses, 50% of FA and mining soil are increased growth parameters, antioxidant parameters, promoting effect on seed germination, high protein content and in 100% of FA and mining soil decreased chlorophyll content, leaf area index, dry weight fresh weight in two wild verities of rice *Oryza nivara* and *Oryza rufipogon*. Mining soil is commonly deficient in essential nutrients which are important for plant growth such as K, P, N and no content organic matter (Bisoi et al., 2017). *Jatropha curcas* grown in FA-amended soil enhanced plant growth and soil quality in 25% to 50% of FA with GS. Three main compounds found in *Jatropha curcas* seed oil analysis are methyl ester, hexadecenoic acid, and linoleic acid. High levels of FA cause high oxidative enzyme activity, which in turn causes high antioxidant enzyme activity (Chhabra et al., 2021). In clay soil poor infiltration and waterlogging occur hence reducing biological properties, in this case, 20% of FA is mixed with clay soil. FA improves soil quality as well as increases the yield and various growth parameters of *Triticum aestivum* in that soil (Dhindsa et al., 2016). Distinct FA concentrations of 20, 40and 60 gm/m^2 and taken from two different genotypes of chickpea JG-14, and JG-11, in range of 20 - 40 gm/m^2 are beneficial for plant growth(Kumar et al., 2021).The impact of FA amendment on soil FA can be used advantageously in agriculture as an agent of acidic soil. The soil in India is alkaline in nature. FA neutralizes soil acidity and improves soil physiochemical and biological activity. FA can alter and enhance soil texture by increasing the percentage of silt-sized particles, water holding capacity and cation exchange capacity electrical conductivity (Hermawan et al., 2023).

4 FA Effects on Soil Health

4.1 Soil plasticity and compaction

The process of decreasing the amount of air in the soil pores to raise soil density is known as soil compaction. These types of soil are ideal for geological building projects, but they decrease plant physiological activity and microbiological activity in agriculture. Soil compaction can occur in a variety of ways at different levels in the soil profiles. Higher bulk-density soil shows compaction; lower bulk density shows less compaction. A healthy soil yields good food and fibre crops, but soil concern occurs when it restricts microbial activity and soil physiological activity as well as the distribution of nutrients such as micro and macro, which has a long-term impact if we do not resolve these issues. The main issue with soil is soil plasticity and compaction. Clay soil shrinks when dry and when wet, hence soil shows flexibility and does not retain its original form. Soil plasticity is not too beneficial for plants and as well as construction and building materials. Soil compaction is another imp soil concern. Soil compaction is defined as an increase in bulk density or a decrease in porosity, as well as reduced air permeability and water filtration and restricted plant root development. Plant roots cannot penetrate the soil layer. So, in agriculture, we utilize FA mixed with expansive soil; however, in construction, we use FA C along with lime, hence the plasticity index of soil decreases (Nalbantoglu et al., 2004). The effect of FA on the bulk density of soil is generally observed to be a reduction in bulk density, though the extent and consistency of this effect can vary depending on factors such as soil type, FA composition and application rate. FA mixture, which is attributed to the pozzolanic reaction of FA. FA addition decreased the bulk density of saline-sodic soils (Sahin et al., 2008). However, some contradictions and interesting facts emerge from the literature. FA treatment did not significantly influence bulk density in their field study on centipede grass (Adriano et al., 2001). This suggests that the effect of FA on bulk density may not be uniform across all soil types or experimental conditions. Additionally, Chen et al., 2016) indicate that for lightweight insulation materials, increasing the content of fine FA particles actually led to an increase in bulk density. The majority of studies indicate that FA tends to decrease soil bulk density; the effect can vary depending on specific conditions and applications. The reduction in bulk density is generally seen as beneficial for agricultural purposes, as it can improve soil structure and WHC. However, the optimal application rate and the long-term effects of FA on soil properties.

4.2 Amelioration of Soil Acidity with FA

pH of the soil has a major influence on the functioning and composition of the microbial communities in the soil. This is important for microbial activity. Because soil fauna grow under different pH values. The acidity and alkalinity of the soil affect microbial activity. The impact of FA inclusion of K, Mg, Ca and oxide on soil pH maintains, which assists in preparing the soil for crops to absorb nutrients in excellent conditions and neutralize soil pH. According to AGRIVI. In an optimal pH many types of metabolic enzymes are activated. FA can be used to increase the pH of acidic soils because of its alkaline character, which is related to its high number of soluble bases like CaO and MgO (Gitari et al. 2008).

4.3 Effect of FA on biological properties of soil

The nutrients produced from the FA amendment may stimulate soil microbial activity. FA application might enhance soil biological activity. Different varieties of beneficial microbes are becoming more prevalent. Many studies show that various FA concentration is related to the proliferation of microorganisms. Beneficial soil microbes carry out essential tasks like cycling nutrients, decomposing crop residues and promoting plant growth. Although it is evident that microbes support crops performance. There are two types of requirements for microbiological growth physical and chemical. Physical factors are osmotic pressure, pH and temperature and chemical factors are water, C, N,O and organic growth factors. FA contains mostly all these factors. FA is used as a soil conditioner however its effect on microbial response and soil enzymatic activities. FA is frequently alkaline, adding it to soil may raise the pH of the soil. Most soil microorganisms have preferred pH ranges which may grow. Highly acidic and highly alkaline can have an impact on the activities of microbial populations. The concentration of trace elements and heavy metals in FA varies based on the coal source certain metals like Hg, Cd can be hazardous to microorganisms at high concentrations of FA. The particle size of FA also affects the soil microorganism. Fine particles of FA alter the growth of microorganisms. FA application was studied in a different pot experiment results shown below (Table 2). FA application was studied in a different pot experiment. *Rhizobium Pseudomonas striata* growth rate increased by 20% and reduced by 40% in FA when mixed with soil in varying FA ratios of 0%, 20% and 40% (Siddique et al., 2005). The ratio of soil and FA (0%, 20%, 40%) *Rhizobium pseudomonas striata has* the highest reduction of 40% and the highest growth rate of 20%. The ratio of FA + *Cassia tora and Meloidogyne incognita* (T1 - *M. incognita*, T2 - *C. tora* + *M. incognita*, T3 - 20% FA + *C. tora* + *M. incognita*, T4 - 30% FA + *C. tora* + *M. incognita*, T5 - 50% FA + *C. tora* + *M. incognita*) in the ratio of T3 and T4 root-knot nematodes development was inhibited and 30% of FA prevented nematodes population and galling (Azam et al., 2013). In ratio of FA and soil (F1 - Control, F2 - 5% FA + 95% Soil, F3 - 10% FA + 90% Soil, F4 - 20% FA + 80% Soil, F5 - 30% + 70% Soil, F6 - 40% FA + 60% Soil, F7 - 50% FA + 50% Soil) root-knot nematodes has lowest inhibition in F2 ratio and highest inhibition in F5 (Ahmad et al., 2016). Microbiota is only minimally impacted by FA concentrations of 5-10%, although soil enzymes and microflora were negatively impacted for an extended period of time by greater dosages (Roy et al., 2011). Reduced pathogen vitality and regrowth with PM + 50% + 4% CaO (Wang et al., 2009).

Table 2 The ideal FA percentage for developing microorganisms.

Combination	Ratio	Microorganism	Optimum % of FA for growing microorganisms	References
Soil + FA	FA - 0%, 20%, 40%	*Rhizobium* *Pseudomonas striata*	Highest reduction in 40% Highest growth rate in 20%	Siddique et al. (2005)
FA + *Cassia tora* + *Meloidogyne incognita*	(T1) *M. incognita* (T2) *C. tora* + *M. incognita* (T3) 20%FA + *C. tora* + *M. incognita* (T4) 30%FA + *C. tora* + *M. incognita* (T5) 50%FA + *C. tora* +*M. incognita*	Root-knot nematode *Meloidogyne incognita*	20-30% FA are decreased nematode growth and 30% FA inhibits galling and egg mass populations.	Azam et al. (2013)
FA + Soil (w/w)	F1- Control F2 - 5% FA + 95% Soil F3 -10% FA + 90% Soil F4 -20% FA + 80% Soil F5 - 30% FA+ 70% Soil F6 - 40% FA+ 60% Soil F7- 50% FA+ 50% Soil	Root-knot nematode *Meloidogyne incognita*	The lowest inhibition of hatching is 5% of FA. Highest inhibition of hatching- 50%, Penetration was reduced due to increased level of FA.	Ahmad et al. (2016)
FA + Soil + Farmyard manure (w/w)	FA- 5%, 10%, 20%, 40% (w/w) soil 10% (w/w) Farmyard manure 10% (w/w)	Bacteria Fungi *Actinomycetes*	FA dosages of 5 to 10 % have a mild impact on microbiota, higher dosages have a long-lasting negative impact on microflora and soil enzymes.	Roy et al. (2011)
FA+ Pig manure + CaO	PM Control 50% FA +2% CaO + PM 33% FA + 2% CaO + PM 25% FA + 2% CaO + PM 50% FA + 4% CaO + PM 33% FA + 4% CaO + PM 25% FA + 4% CaO + PM	*Salmonella* *coliform*	PM + 50% + 4% CaO Reduced the vitality and Re-growth of pathogens.	Wang et al. (2009)
FA + Soil	FA- 5%, 15%, 20%, 25%	*Meloidogyne incognita*	*M. incognita* was negatively impacted by all FA concentrations.	Haris et al. (2025)
FA + Soil	FA -5% + *M.incognita* FA -10% + *M. incognita* FA - 15% + *M. incognita* FA - 20% + *M. incognita* FA - 25% + *M. incognita* FA - 30% + *M.inconita*	*Meloidogyne incognita*	*M. incognita* was negatively impacted by all FA concentrations.	Haris et al. (2024)

5 Effects of Class-C and Class-F - FA on Soil Properties

Based on its origin and chemical makeup, FA is divided into two primary categories (Class-C and Class-F). Burning bituminous or anthracite coal produces Class-F FA, whereas burning lignite or sub-bituminous coal usually produces Class-C FA (Tennakoon et al., 2015; Turan et al., 2022). Class-C FA is more reactive in concrete mixes due to its increased calcium concentration and self-cementing qualities. Class-F FA has less Ca (Turan et al., 2022). Although both Class-C and Class-F FA have potential uses in the agricultural sector, it indicates that Class-C FA is more advantageous for crop productivity and soil enhancement. Due to its high CaO concentration, Class-C FA exhibits better self-cementing qualities and is more effective in stabilizing soil (Misra, 1998). Applying Class-C FA on expansive soils improves the soil characteristics more effectively. Although Classes C and F FA are both used in agriculture, Class-C FA seems to be more useful for improving the soil because of its greater calcium content and self-cementing qualities. To ensure safe and advantageous use in plant production systems, the decision between the two should be based on particular soil characteristics, crop requirements, and environmental factors. (Table3) shows many oxides that are found in classes C and F FA. Class-C and Class-F FA have distinct oxide compositions that affect their characteristics and their use in the agriculture sector. The oxide compositions of Class-C and Class-F FA, namely the amounts of SiO_2, Al_2O_3, and CaO, are the main differences between them. Variations in reactivity and strength development. Class-C FA could be more effective in neutralizing the acidity of the soil and enhancing its structure due to its higher calcium content. Class-F FA, which is high in silica and alumina, can improve soil water retention and supply vital micronutrients.

Table 3 Composition of Oxides in Class-C and Class-F FA (Bentz et al., 2010).

Chemical analysis	Class-C FA (%)	Class-F FA (%)
SiO_2	38.38	59.73
CaO	24.63	0.73
Al_2O_3	18.72	30.18
Fe_2O_3	5.06	2.80
Na_2O	1.71	0.24
MgO	5.08	0.83
K_2O	0.56	2.42
P_2O5	1.24	0.08

6 Toxicity of FA

FA dumped in FA dykes. The biodiversity of fertile land changes and becomes barren. Only resilient plants and animals will survive in barren environments (Shrivastava et al., 2007). FA contains different types of heavy metals, such as Se, Al, Pb, Hg, Cr, and oxides (SO_3, Fe_2O_3, Al_2O_3, K_2O, CaO, TiO_2), and trace elements. These oxides and heavy metals are toxic to the environment and human health. Threats to human health and the environment from burning plants are hydrated in rainwater and transformed into the corresponding acids (H_2SO_4, HNO_3, H_2CO_3). This disrupts all living kingdoms, including bacteria, archaea, and eukarya, and has several negative effects on the environment and human health. A coal-burning power plant emissions of CO and CO_2 into the atmosphere significantly contribute to global warming, harm the food chain, and accelerate the development of respiratory illnesses, including asthma, cardiovascular disorders, and malaria. Numerous parameters, including salinity, pH, toxicity of metals, and other trace elements and unfavourable circumstances, might restrict the ability of microbes and plants to colonize the FA (Carlson et al., 1993). FA may include contaminations such as PAHs and heavy metals, depending on the coal source of the combustion procedure. The quality of the soil and water may be in danger from their pollutants. FA contains beneficial trace elements as well as they also contain harmful elements such as Se, As, and B overabundance of these elements in the soil can harm plant development and might be harmful to the ecosystem. The experiment examined the leaching behaviour of hazardous substances, including trace elements such as B, V, Cr, Se, Mo, and W leached in significant amounts into pure water, indicating their high mobility (Tian et al., 2018). On the other hand, every kind of coal naturally contains Hg. However, some Hg remains in the coal by-product after burning, releasing some mercury into the environment, and it affects plant growth (Gustin et al., 2004).

6.1 Radionuclides and trace elements in FA

FA is a residue of burning pulverized coal in power plants. The radioactive contaminants in FA are mostly related to the coal that is used to make the ash. A can include trace amounts of radioactive elements. There are important sources of exposure to naturally occurring radionuclides in the FA and bottom ash. Similar to other geological materials, coal includes trace quantities of naturally occurring radionuclides and their byproducts. When these radionuclides are burnt in coal-fired thermal power plants, the radiation is released into the atmosphere. The surrounding population is exposed to radioisotopes that naturally occur through deposition and inhalation due to emissions from thermal power (Mc Bride et al., 1978). The number of radionuclides released into the atmosphere is determined by the radionuclide content in coal. The power plant and the physical and chemical characteristics of the coal determine the specific activity in FA. This rises as the FA particle size decreases. Minerals undergo heat breakdown, agglomeration, disintegration, and fusion throughout the coal-burning process; the majority of the trace elements, such as As, Hg, Cd, and Pb, are found in bottom ash, and volatile elements are released into the atmosphere. So biological and environmental concerns. FA radioactive concentration must be described and quantified. It's crucial to remember that FA can vary in its amount of radioactivity, and not all FA is highly radioactive.

6.2 Persistent Organic Pollutants (POPs) in FA

Organic components in the coal ash might be harmful to the environment. Organic pollutants are made up of two structures: (i) a macromolecule phase with condensed aromatic and hydroaromatic units that are the dominant components and an insoluble (ii) molecular phase made up of low to medium molecularmass, soluble (Liu et al., 2000). When coal is burnt, organic materials are released into the air that, through cyclization or a radical condensation from PAHs,. Similarly, when carbon is burnt in the presence of chlorine constituents from PCBs, both are persistent organic pollutants, and these pollutants are carcinogenic and mutagenic. It has been shown that weathered FA has a very low content of organic pollutants (Jambhulkar et al., 2018). FA from a variety of industrial operations frequently contains POPs. In FA samples, organic contaminants at ppb levels have been found and measured using gas chromatography-Orbitrap mass spectrometry (Yang et al., 2019).

7 FA Application-Related Threats in Agriculture

FA contains various heavy metals such as Pb, Hg, and As. FA is an appropriate amount that enhances soil quality and crop yield. FA contains micro and macro elements and toxic elements such as Cd, Mn, Zn, Mo, As, Cu, Hg, and Ni. Consumption by animals and humans through the food chain causes health risks (Yunusa et al., 2012). Heavy metal concentration in FA depends upon the processing of coal burning, particle sizes, and the area of coal mining. The highest concentration of heavy metal content in groundwater was observed during the period of precipitation. The main factor that determines heavy metal leaching from ash ponds is pH instead of the amount of FA (Verma et al., 2016). The amount of FA is directly proportional to microbial activity. When FA is applied in excess, it inhibits soil enzyme activity because it reduces substrate availability, and it also affects soil invertebrates. Another major problem that is associated with soil, FA alkaline properties can help acidic soil overuse and cause the soil to become alkaline, harming some crops. High doses of FA suppressed the growth of crops, but low doses of FA increased the growth of crops and yield. Despite its many benefits as a soil supplement, the use of FA in agriculture has several possible risks. FA-associated radioactive elements and hazardous heavy metals are the main causes for concern (Singh et al., 2010). These pollutants may have detrimental long-term effects on the ecosystem, crop quality, and soil health. While FA can increase crop yields and soil fertility, it also poses a danger of heavy metal toxicity and leaching when used in excess, which is one of the primary issues in its application (Singh et al., 2010). According to Hansen et al. (2001), research on FA from burning straw revealed that around 50% of the cadmium concentration was water-leachable, which might potentially contaminate groundwater and affect plant uptake.

8 Conclusion

FA, the solid waste product of thermal power plants, is currently a significant issue. India produces more FA than other countries due to its population. Due to concerns about climate change, holder farmers are facing a variety of agricultural challenges because fertilizers are expensive, so farmers cannot afford them. FA and industrial waste products are used as soil fertilizers because they have the potential to significantly improve crop yield and soil health. An effective way to reduce waste and enhance soil quality in agriculture is to use FA. Numerous investigations have exhibited its capacity to improve soil quality and increase crop yields. FA can be used strategically to enhance agricultural soil physical and fertility restrictions, as well as their acidity. FA can be used on farms as a cheap substitute for some fertilizers and liming ingredients if it is chosen correctly and administered at the right concentrations. To prevent phytotoxicity from excessive trace metal concentrations, however, while preserving produce quality and lowering environmental hazards, it is imperative to take the soil and crop type into account. Numerous academics and researchers are looking for novel ways to convert FA into profitable products in the agriculture sector because of limited FA uses in agriculture. FA is currently recognized as a significant soil conditioner, and their standard amount of FA enhances plant productivity and development. FA mixed with different organic and inorganic materials are safe and alternative source of fertilizers. Although FA may be useful in agriculture, its composition and application rates need to be carefully considered. Reclamation and revegetation techniques must be implemented successfully in order to convert FA dumping sites into environmentally beneficial landscapes. Phytoremediation, biotechnological methods, and organic amendments have demonstrated potential in stabilising pollutants and improving soil qualities. Native plants are essential for eco-restoration initiatives because of their resilience. Continued study and sustainable management techniques can turn FA from a waste byproduct into a useful resource that helps in land rehabilitation and environmental restoration. Monitoring the effects of FA on soil properties, heavy metal absorption, plant physiology, and crop quality requires long-term research.

Abbreviations

FA- FA
WHC – Water Holding Capacity
NF- Nitrogen Fertilizers

BGA- Blue Green Algae
MR- Mycorrhiza
GS- Garden soil
CD- Cow Dung
Polycyclic Aromatic Hydrocarbons- PAHs
Polychlorinated Bio Phenyls- PCBs
Central Pollution Control Board- CPCB
Ministry of Environment Forests and Climate Change- MoEFCC.

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