REVIEW ARTICLE

# Integrated Use of Fly Ash, Blue-Green Algae, and Bio-Fertilizers for Sustainable Rice Cultivation in Fly Ash-Contaminated Environment

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## Abstract

The coal-fired power plants generate a high volume of fly ash (FA), a significant solid waste with considerable environmental and health consequences. The stagnation of FA around heat-generating factories causes pollution due to toxic heavy metals. These pollutants jeopardize biodiversity, disrupt ecosystems, and pose a serious threat to human health, and agricultural crop land contaminated by FA, such as rice (*Oryza sativa* L.). Despite FA having some effective plant nutrients (Ca, S, B, Mo, Cu, Zn, and Fe), it has deficiencies of essential nutrients such as N, which makes it ineffective as a direct fertilizer. However, green algae, a population of nitrogen-fixing photosynthetic microbes that grows in paddy fields, is the answer to it. Some heterocystous strains are the ones that rely on the B availability in FA to enhance maximum fixation of N. This paper undertakes a synergistic application of green algae and FA, and chemical fertilizers to improve soil fertility, reduce heavy metal toxicity, and promote sustainable disease-resistant rice production on the FA-contaminated land, emphasizing heavy metal bioaccumulation, detoxification, and bioremediation. The combined approach is sustainable, cheap, and eco-friendly in terms of FA waste management, which is in line with the principles of the circular economy, and restoring the environment and securing food in the future.


**Keywords:** Agriculture, BGA, Fly-ash, Plant growth.

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## Introduction

In India, coal still continues to dominate energy production, and around 75% of our energy requirements are supplemented by thermal power plants. The use of pulverized coal burning, however, produces enormous amounts of fly ash (FA), an industrial by-product that has agronomic potential and environmental hazards. FA is also a good source of nutrients like Fe, Zn, Ca, and Mg, yet it has toxic elements like Pb, Cd, Hg, and As that are dangerous to the environment unless it is well managed (Carlson and Adriano, 1993; Gupta *et al*., 2002; Pandey and Singh, 2010; Pandey *et al.,* 2009a). The coal in India is rich in ash (>30%), resulting in the production of about 120 million tonnes of FA per year, and this may reach 150 million tonnes (Dwivedi *et al*., 2006). Although about 15% of FA is currently recycled, far lower than in developed countries such as Germany (85%) and the USA (32%), a large proportion remains underutilized, with only partial use in industries such as cement and road construction (Sinha and Basu, 1998; Jala and Goyal, 2006). The rest is discarded in landfills, which pollute the soil and water sources by leaching metals, crippling plants, and leading to instability of the ecosystem (Sikka and Kansal, 1993). According to recent research, the potential uses of FA in agriculture include a better texture, porosity, the capacity to retain moisture, and the activity of microorganisms in soils (Lal *et al*., 1996; Mittra *et al*., 2005; Pandey *et al.,* 2009a). But in excess use, they may cause the soil to be salinized, along with the loss of nitrogen that is harmful to plant growth (Kalra *et al*., 1998).

Rice, the staple food crop in India, is very sensitive to the quality of soil. FA is a potential source of silica, which is one of the nutrients of rice, but the impact of FA on the high-yielding rice cultivars is also not fully studied. This is of particular importance in areas such as Uttar Pradesh, where lands contaminated with FA are usually farmed with paddy. Specific screening of local varieties of rice in terms of their FA tolerance and productivity is necessary to provide sustainable agriculture and support a healthy environment due to the application of FA. The multifunctional uses of algae have generated a lot of scientific interest because of their environmental sustainability. Algae, which were formerly appreciated because of their nutritional

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value in terms of protein (Venkataraman and Rajyalakshmi, 1972), have since been extensively used in the treatment of sewage, pollution control and bio-fertilization (Rao and Alexandra, 1985). They are sensitive to pollutants, which makes them good bio-indicators and phyto-toxicity assay organisms that can be used in the monitoring of the aquatic ecosystem (Mohamed, 2001; Tien, 2002). Algae also aid in stabilizing water bodies by eliminating inorganic elements of heavy metals through carboxyl group surface adsorption as well as through intracellular chelation by polysaccharides (Kaplan *et al*., 1987; Zhang and Majidi, 1994). An example of such a survival mechanism is Synechocystis, which develops a protective calyx in copper stress (Gardea-Torresdey *et al*., 1996), and *Synechococcus* sp., which removes copper by ATPase pathways (Bonilla *et al*., 1990). Strains such as *Synecococcus cedrorum* are resistant to both metals and pesticides, and this adds to their bioremediation potential (Gothalwal and Bisen, 1993). Green algae (GA) have been demonstrated to be capable of removing heavy metals in FA-contaminated environments that are highly toxic, such as Cd, Ni, and As (Gupta *et al*., 2002; Jala and Goyal, 2006). In FA-impacted agriculture, nitrogen-fixing BGA, such as Anabaena, enhance the fertility of the soils, particularly where there is a lot of boron. Nonetheless, to use metal safely and effectively, toxicity screening of tolerant strains is required (Lopez-Maury *et al*., 2002). Although the benefits of BGA are well established in rice fields, literature on its synergistic effects in FA-contaminated rice field are limited. Furthermore, the mechanism of accumulation, detoxification and remediation of toxic heavy metals in soil has not yet been compiled together for systematic presentation, particularly in rice ecology.

## Fly ash (FA)

Silica, alumina, and iron oxide are the major components of FA, a product formed by the coal burning in thermal power plants, making it a ferro-alumino-silicate material (Adriano *et al*., 1980; Mattigod *et al*., 1990; Pandey and Singh, 2010; Pandey, 2020). It is composed of varying quantities of coal depending on the source of coal and, in most cases, traces of various elements, including boron, cadmium, chromium, arsenic, lead, and zinc (Kaw *et al*., 1990; Saxena *et al*., 1995; Pandey *et al*., 2011; Pandey, 2020). FA is structurally heterogeneous, being made of amorphous and crystalline phases (El-Mogazi *et al*., 1988), and its fine particle size is improved, increasing its surface area and reactivity. Due to its pozzolanic nature, FA forms cementitious compounds with water and calcium, which makes it suitable for use in brick manufacturing. Besides its industrial use, FA has also been offered in the agricultural sector owing to its composition of plant-essential macro- and micronutrients. Research indicates that it can be amended to soil to improve its structure, nutrient availability, and yield more crops (Wong and Wong, 1989; Sikka and Kansal, 1993). FA is a viable solution for transforming waste and enriching soil fertility with its proper use and control. As it is a by-product of coal burning in thermal power plants, it exhibits considerable variation in physical and chemical properties, depending on the coal source, combustion conditions, and emission control measures (Page *et al*., 1979). The percentage of FA particles constitutes a significant proportion of fine particles in the silt and clay size range (<53 µm), which increases their contact with the soil system (Wong and Wong, 1989). FA also has vital components of plant nutrition like iron, calcium, and sulphur; other toxic components like cadmium, lead and arsenic also exist, and they are dangerous to the environment due to their leaching qualities (Carlson and Adriano, 1993). Nevertheless, FA has the potential of enhancing the soil structure, porosity, water-holding capacity and the corresponding microbial activity in coarse or degraded soils (Ghodrati *et al*., 1995; Lal *et al*., 1996; Pandey, 2020). It is alkaline (pH: 8.5-12.5) and can therefore serve as a liming agent to acidic soils (Maiti *et al*., 1990). Lack of nitrogen (N) renders FA to be complemented with N sources to ensure the growth of the plant (Bern, 1976; Khandekar *et al*., 1993). Bio-amendments of soils with BGA provide an attractive bioremediation approach to FA-contaminated soils because this algae has the capacity to fertilize soils and trap heavy metals that ecologically reduce toxicity and offer agricultural sustainability.

## Uses of FA

The FA, a by-product of coal combustion, is widely used in the cement and concrete sector, but it has a lot of potential in agriculture and ceramic production (Anderson and Jackson, 1983; Queralt *et al*., 1997; Pandey, 2020). Studies have shown that in small doses, FA does not create significant danger to soil microflora and the food chain at large (Carlson and Adriano, 1993; Saxena *et al*., 1998). FA increases the physical and chemical characteristics of soil, such as texture, water-holding capacity, and pH equilibrium in agriculture, which are necessary to increase total crop yield (Patil *et al*., 1996; Sugawe *et al*., 1997). Besides, it is a valuable source of K and P (Its alkaline property may be of great use, especially in counteracting the acidic soil as well as its nutrient content, which favours plant growth. Despite such benefits, the rate of utilization of FA in India is still low (less than 10%) in comparison with more than 70% in some developed states (Dwivedi *et al*., 2007). This poor use has led to significant levels of disposal problems, whereby huge amounts of FA are deposited in landfills around thermal power plants, which cause land degradation and contamination of the environment. Increased application of FA in agriculture and industry would reduce the disposal issues and enhance sustainable development, although this needs more awareness, friendly policy and facilities on how to handle safe and efficient disposal of FA.

## FA-mediated microbiological properties of soil

FA, a by-product of coal combustion, exerts dose-dependent effects on soil microbial activity and nitrogen fixation, with both positive and negative outcomes. At low to moderate concentrations, such as 8%, FA has been shown to enhance nodulation, increase nitrogen content, and stimulate microbial activity (Lal, 1994; Vajpayee *et al*., 2000; Rai *et al*., 2004). This is attributed to the presence of essential nutrients and improved soil aeration. FA has also been found to be a better carrier material of rhizobia inoculants compared to the conventional substances such as sand and charcoal to promote legume symbiosis (Ghosh *et al*., 1996). Additionally, FA supplementation with organic amendments positively affects the quality of microorganisms and soil (Lal *et al*., 1996; Lee *et al*., 2006). Nonetheless, when FA is used at high levels, its effect on microorganisms is destructive, and it reduces the activity of the entire ecosystem (Carvelli *et al*., 1986; Arthur, 1984). This is probably because of the deposition of toxic elements, like the heavy metals, which suppress the functions of the microbes. Consequently, FA has the potential as a soil amendment and microbial proliferator. Nonetheless, FA when used in moderate quantities ameliorates the soils that are contaminated with heavy metals due to several similarities with soil and owing to the existence of important micronutrients like B, Cu, Zn, Fe, Co, Mn, and Mo, and macronutrients like S, K, P, Ca, and Mg. It is also used in the reclamation of wastelands (mine spoil) due to its capacity to act as a buffer against the presence of wastelands in the soil, such as lime and gypsum (Jangde *et al*., 2024). It serves as a transporter of nitrogen-fixing and phosphate-solubilising or fixation bacteria like *Azotobacter chroococcum*, *Azospirillum brasilense,* and *Bacillus circulans* (Gaind *et al*., 2004) as well.

## FA on agriculture

FA can also replace lime in agriculture because lime is a heavy producer of $CO_2$ (Chen *et al*., 2004; West *et al*., 2005). FA, thus, reduces global warming by changing the ecological way of farming. FA is applied in various ways in the field of boosting crop yield, and it replaces chemical fertilizers and turns out to be a blessing in agriculture (Jangde *et al*., 2024). Silicon is one of the elements found in large quantities in the FA that enhances the Si level in the rice crop and promotes its growth (Lee *et al*., 2006). FA is highly suggested to be used in the agriculture field due to its constituents such as potassium, calcium, magnesium, Sulphur and Phosphorous (Shiman *et al*., 2017). A test was carried out to determine that sorghum (*Sorghum bicolor*), alfalfa (*Medicago sativa*), carrots (*Daucus carota*), beans (*Phaseolus vulgaris*), tomatoes (*Solanum lycopersicum*), etc., could be easily cultivated in acidic soil (pH 6.0) and added with 125 mt/ha unweathered FA. Surveys conducted by Stoewsand *et al*. (1978) proved that selenium-rich grains were produced by the winter wheat (*Triticum aestivum*) on a field with FA. Khan *et al*. (1997) report that FA 14% has a nematicidal effect and could be used in the treatment of root-knot disease of the tomato crop caused by *Meloidogyne sp*.

The impact of FA on the growth of plants, the uptake of metals and soil enhancement has been researched in many studies. Tripathi *et al*. (2004) observed that plants that died in FA supplemented with press mud, followed by cow dung, had high levels of metals, and this trend was attributed to the low pH and high metal solubility. When the level was low (0.51%), it caused low effects on the germination of corn and soybean, but higher levels prevented growth (Shukla and Mishra, 1986). With FA foliar application to *Dolichos lablab*, Dubey and Pawar (1985) observed a higher chlorophyll and lower dry weight of the leaves. Wong and Wong (1989) indicated that Brassica species germinated better at low levels of FA and were inhibited at more elevated levels. Composts enriched with FA had a positive effect on the yield of collard and mustard (Menon *et al*., 1993), and did not affect species such as eggplant and bell pepper. FA at 1.5 $kg/m^2$ increased the growth of sunflower (Pandey *et al*., 1994) and increased the biomass of *Lactuca sativa* to 10% FA. FA also contributed to the increase of *Morus alba* (Singh and Yunus, 2000) and the relevance of crop yields such as okra and colocasia (Kumar *et al*., 2000). Nevertheless, one must be cautious because Sarkar *et al*., (2000) cautioned about the elevated heavy metal concentration in edible portions with elevated FA levels. Pandey *et al*., (2009b) showed that a lower concentration of FA (25%) is safe for *Cajanus cajan* cultivation, which not only enhanced the yield significantly but also ensured heavy metal translocation to edible portions within the critical limits. The effect of FA on the growth and yield of many plant species has been reported.

Although FA can be amended in soil with significant potential because of the nutrients it contains, there is a need to manage its use in agriculture. Possible issues that have been highlighted are contamination of the groundwater by leaching of toxic elements, slowness of germination in high levels of FA and plant accumulation of heavy metals. However, research points to its beneficial effects. According to Kumar *et al*. (1998) and Mendki *et al*. (2001), there were no adverse effects with pulse crops, and FA was also shown to be effective in pest control in soybean. Field trials in the Punjab Agricultural University (PAU) showed significant increases in the yield of brinjal, potato, pea, tomato, wheat, and cotton with the application dose ranging between 10 and 25%. FA of 10 t/ha increased the yield of rice and groundnut by 14 and 26%, respectively (IIT, Kharagpur), and improved the soil productivity when used together with sludge and fertilizers. Similar positive effects were observed in rice-mustard systems with pond ash. However, its reactions with crops differ despite such advantages. According to Kalra *et al*., (1997), rice, maize and mustard have better tolerance to FA with respect to germination, delayed emergence and low establishment, respectively. Such variability highlights the necessity to engage specific protocols of applying FA to crops to maximize the benefits and reduce the risks related to the heavy metal contamination in soil.

## FA on rice crop

Integrated nutrient management (INM), which involves FA, organic wastes and chemical fertilizers, positively affects the productivity and soil quality of rice. Recently, Pradhan *et al*. (2025) suggested that the combination of FA (20–40 t $ha^{-1}$) with FYM (Farmyard manure) and NPK can improve soil functionality and sustain rice productivity. Singh *et al.* (2011) reported that FA and FYM can be used as potential amendments to enrich soil productivity and crop yields for dry tropical nutrient-poor soils. Singh and Pandey (2013) reported that FA at lower doses with press mud seems to offer the potential amendments to improving soil methanotroph population and paddy crop yields for the nutrient poor agriculture soils.

Significant increases. In available phosphorus (48%) and organic nitrogen (ON, 0.29%) at 20 t/ha FA application rate (Sarangi et al., 2021). The benefits were improvement in soil properties with increased pH, organic carbon and nutrient availability (N, P, and K). Lee *et al*. (2006) also demonstrated the advantage of FA on different soils due to silicon (Si), which supports rice to gain nutrition, with resistance to diseases and volatility. FA has demonstrated great efficiency in Korea, where there is widespread Si deficiency with less silicate fertilizers; more Si in the soil is available, which enhances phosphorus and boron, thus improving yield. Dwibedi *et al*. (2021) experimented on FA and vermicompost (VC) application at different concentrations in rice nursery and reported the maximum plant height at 40 DAS with 80% VC + 20% FA, followed by 40% soil + 20% FA + 40% VC. Plant biomass was also maximum in the latter combination at 40 DAS. In Table 1, the benefits of FA addition at different concentrations in different soil types are depicted, citing the enhancement of yield in different crops. Heterocystous BGA (e.g., *Anabaena, Tolypothrix*) sequester nitrogen in the atmosphere in flooded rice fields. In anaerobic conditions, non-heterocystous strains (e.g., *Oscillatoria, Lyngbya*) are also contributors and resilient to agrochemicals. BGA is a viable technology to improve the fertility and to overcome the environmental stress caused by FA in the rice agroecosystem.

## FA on plant growth

While FA has recognized agronomic potential, its application at higher concentrations can negatively affect plant growth and soil health due to elevated alkalinity and salinity (Hodgson and Holiday, 1966). Light exposure also influences plant response; Tripathi and Tripathi (1998) observed that *Acacia nilotica* tolerated both light and shade in FA-treated conditions, while *Albizia procera* showed increased biochemical defences under light. The physical and chemical characteristics of soil are considerably altered by FA incorporation (Pandey 2020). Bulk density declined, water-holding capacity and organic carbon spiked (Garg *et al*., 1996; Kalra *et al*., 1997, 1998). Applying FA (10 t/ha) to sandy loam soil at IARI enhanced the growth of maize roots and the wheat yields in the maize-wheat system. Chemically, FA can elevate soil pH up to 9.9, depending on ash characteristics (Adriano *et al*., 1982; Page *et al*., 1979). FA use also enhanced available water content by 120% in loamy sand and 67% in sandy soils (Singh and Kansal, 1994), while improving porosity in black soils and reducing surface crusting in red soils. For the safe and efficient use of FA, region-specific assessments are necessary because long-term effects on soil biology and heavy metal mobility are still unknown. Table 1 shows the effect of various fly ash doses on the growth and yield of a number of plants in detail.

## FA on human health and environment

As FA improves the physical and chemical properties of soil, it has significant potential as a soil amendment. Tripathi and Tripathi (1998) discovered that *Acacia nilotica* demonstrated tolerance under both light and shade conditions in FA-treated conditions, while *Albizia procera* showed enhanced biochemical accumulation (e.g., ascorbic acid, proline) in light, indicating stress adaptation. However, excessive application can result in elevated soil alkalinity and salinity, negatively affecting crop growth and microbial health (Hodgson and Holiday, 1966). FA incorporation improved soil structure, improved water retention, higher levels of organic carbon and decreased bulk density (Garg *et al*., 1996; Kalra *et al*., 1997, 1998; Pandey, 2020). Applying FA to sandy loam soil improved the performance of maize and had long-lasting effects on wheat in the subsequent season. FA can dramatically increase the pH of soil chemically, reaching 9.9 at 8% application (Adriano *et al*., 1982; Page *et al*., 1979). Additionally, FA decreased surface encrustation in red soils while increasing water availability and porosity, particularly in loamy and black soils (Singh and Kansal, 1994). Despite these advantages, additional crop-specific and region-specific evaluations are required due to the long-term effects on soil biological health and heavy metal mobility. Dwibedi *et al*. (2021) have reported the presence of more earthworms at 20% soil + 20% FA+ 60% VC (250.8/$m^3$), followed by 60% soil + 20% FA+ 20% VC with 124.4 counts. However, the earthworm count was maximum in the absence of FA in the rice nursery soil. The population of *Rhabditis terricola* and *Dorylaimida sps* in rice soil declined with the increase in FA concentration from 0 to 100%. No nematode was found in rice nursery soil with 100% FA. However, FA toxicity was moderated gradually with the increase in VC concentration in soil. Higher $CO_2$ efflux from rice nursery soil could be due to a gradual increase in VC concentration moderating FA toxicity. A strong correlation existed between rice seedling growth and soil physicochemical parameters in FA-amended soil (Dwibedi *et al*., 2021).

## FA on metal accumulation

The application of FA to agricultural soils significantly influences the uptake and accumulation of trace metals in plants; the impact differs depending on plant species, type of soil and composition of FA. There is a tendency for reduced Zn availability after FA amendment. According to Page *et al*. (1979) and Elseewi *et al*. (1980), the decreased uptake of Zn in alfalfa, barley, Brassica, bottlebrush species and rice was also reported in Sikka and Kansal (1993). Conversely, Cu reactions were sporadic, due to some studies depicting high levels of increase in uptake among corn and soybean seedlings (Shukla and Mishra, 1986), others described non-significant or inconsistent impacts (Sikka and Kansal, 1993; Singh *et al*., 1996). There was also variability in the uptake of Fe depending on soil types (Page *et al*., 1979). The Mn tended to decrease during FA treatment, especially in acidic soils, although with a small but significant increase in calcareous conditions. Accumulation patterns showed higher concentrations in roots than shoots, particularly for Fe and Mn (Sarkar *et al*., 2000). Pb, Ni and Co concentrations rose with higher FA levels, raising food safety concerns (Singh *et al*., 1996; Kumar, 1998). These findings signify the importance of regulated FA application and crop-specific guidelines to mitigate metal toxicity risks.

## Risk framework analysis

Bioavailability and metal mobility of relatively stable phases of heavy metals are influenced by soil properties such as pH, organic matter content, redox conditions, and cation exchange capacity. The accumulation of such metals in different plant parts released from FA is species dependent and mostly channelized through roots and stored in edible parts (Crespo-Toledo *et al*., 2025). Leafy vegetables and root crops accumulate higher concentrations of metals compared to cereals, with some exceptions (As in rice). In terrestrial food chains, heavy metals enter humans and animals diets through such contaminated plant foods. Once absorbed, these metals bio-accumulate in tissues and bio-magnify at higher trophic levels. Persistent exposure to HM-contaminated diets is linked to neurotoxicity, renal dysfunction, carcinogenesis, developmental disorders, and immune suppression. Instances of chronic Cd exposure are associated with kidney damage and osteoporosis, and Pb exposure in developing nervous disorders (Rasin *et al.*, 2025).

Risk analysis frameworks are essential to assess and manage these impacts through a) Hazard identification, by ascertaining the toxic heavy metal presence; b) Exposure assessment, quantifying dietary intake through measured metal concentrations in food; c) Dose–response assessment, using toxicological reference values; and d) Risk characterization, calculating Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) to assess carcinogenic risks (Singhato *et al.*, 2025). Source-level limitation of pollution, adoption of improved agronomic practices, and soil remediation are critical. Techniques such as phytoremediation, soil amendments, stringent regulation on water quality, and breeding for lower uptake significantly reduce their uptake. Furthermore, algal cultivation has potential for bioaccumulation, detoxification and remediation of heavy metals.

## Algal periodicity with water quality

The tropical climatic conditions, especially after the monsoon, leave the cyanophycean (blue-green) algae to thrive effectively in aquatic environments like rice paddies, ponds and lakes (Venkataraman, 1979). These genera, such as *Anabaena*, *Nostoc*, and *Gloeotrichia,* are the most prevalent ones in September-November, whilst Oscillatoria and Lyngbya are prevalent across the climates, flourishing even with polluted or low-oxygen waters (Zafar, 1964a, b). The water hardness, salinity and nutrient levels are some of the factors that affect their abundance and assortment. The cyanobacteria, such as *Microcystis aeruginosa*, are found in eutrophic regions, particularly the nutrient-containing littoral regions (Ali *et al.*, 1999). Their strength and metal bio-sorption ability make them good bioremediation agents. Nonetheless, the augmenting urbanization and contamination by FA effluents and sewage are endangering the aquatic biodiversity by interfering with the superstructure of the algal community (Dwivedi *et al.*, 2006). The reaction of algae toward heavy metals varies according to species and type of metal, where some are required in limited trace levels, whereas others are also toxic when in excess (Round, 1973; Noda and Horiguchi, 1971).

### Metal accumulation by cyanobacteria

Cyanobacteria are considered useful model organisms for assessing environmental toxicity because they are primary producers and also sensitive to pollutants (Lee *et al.*, 2002). They are the best agents in the bioremediation process due to their heavy metals bio-accumulative ability and the amount exceeds that of the environment (Becker, 1986). Other species, such as *Anabaena doliolum,* do not release the metals such as Ni, Fe and Mn into the soils as well as enhance the soils' fertility (fixation of nitrogen and mobilization of phosphorus) (Rai *et al.*, 2000). Strains like *Nostoc commune* and *N. calcicola*, *Microcystis aeruginosa* can store various metals and indicate the existence of Cr without being detectable in water (Ali *et al.*, 1999). Genetically engineered *Nostoc* strains exhibited an improvement in Cd uptake (Ravendra *et al.*, 2002). There are others, such as *Westiellopsis* and *Plectonema boryanum,* which exhibit extraordinary levels of metal resistance and uptake efficiency. Algal biosorption acts as an alternative and cost-effective way of treating wastewater sustainably. Arsenic accumulation, detected in $FA_{100}$ amendments, was reduced with the $BGA_{12.5}$ inoculation along with a reduction in Ni and Cd (Tripathi *et al.*, 2008). Jaiswal et al. (2023) advocated for the engagement of *Chlorococcum sp.* for FA-amended soils, enhancing biomass and lipid production, and nutrient recovery from FA.

### Metal detoxification by cyanobacteria

Different biochemical processes are used by green algae and cyanobacteria to detoxify heavy metals, and they play a crucial role in the elimination of wastes present in the bioremediation of water. The toxic metals, such as Cd, are chelated by green algae using enzymatically synthesized phyto-chelatin-thiol-rich peptides, which include coordination of the toxic metal by thiolato complex (Grill *et al.*, 1985; Grill *et al.*, 1989). In the same way, cyanobacteria express metallothioneins like SmtA, which selectively bind Zn with both cysteine and histidine residues, which are judgments of both metal-specific binding systems. Cadmium-111 nuclear magnetic resonance (NMR) experiments suggest varied Cd-binding geometries, further indicating the fact of adaptations to metals. Oxygen-evolving photosynthetic organisms are also beneficial in detoxification through the accumulation of pollutants with the aid of high ratios of surface to volume and carbon uptake. Cyanobacteria like *Anabaena*, *Nostoc*, and *Oscillatoria* degrade nitrates, phosphates and even aromatic pollutants through pathways such as hydroxylation and methylation. Strains such as *Aulosira fertilissima* metabolize organophosphates aided by phosphate-solubilizing enzymes.

### Detoxification mechanism in BGA

Cyanobacteria have amazing metal ion binding capabilities due to two major systems involving passive bio-sorption and active bioaccumulation (Kama *et al.*, 1999). Bio-sorption is based on charge-mediated attachment to the cell wall of the metals (especially the mucilage containing a lot of exopolysaccharides), where there are many metal-binding sites. Bioaccumulation, on the other hand, internalizes the transport of metals by energy-dependent transport. Metals are intracellularly stored either in polyphosphate granules or bound by metallothionein-like ligands (Jensen *et al.*, 1982; Olafson *et al.*, 1980). Cyanobacterial metallothioneins (MTs) are producible proteins of the Class II type comprising approximately 56 amino acids each containing nine cysteine amino acids, which allows selective binding of both essential (Zn, Cu) and poisonous metals (Cd, Hg, and Pb) through thiol clusters (Turner *et al.*, 1995). It is also common to increase the expression of the MT genes in response to Cd and other metal stress, especially in the strains of the polluted environment (Gupta *et al.*, 1992). These cyanobacteria's strategies of detoxification emphasize that cyanobacteria are particularly resilient under evolutionary conditions and have a capacities-based view of application in bioremediation applications.

### Cyanobacteria as a bio-fertilizer

There is growing appreciation of the significance of sustainable farming, and BGA has a pivotal role to play in combined nutrient management, particularly in rice farming. Research conducted in India has proven that a BGA application rate of 12.5 kg/ha, in addition to 90 kg N/ha as Urea, produces the same grain and straw production as 120 kg N/ha as Urea does. Synergistic interaction of BGA with green manure, especially *Sesbania rostrata,* enhances field crop productivity. The combination of *Sesbania* and BGA at a low input of 30 kg N/ha resulted in an equivalent yield compared to 90-120 kg N/ha of inorganic nitrogen, which led to the realization that chemical fertilizer consumption could be cut down (Rao *et al.*, 1998; Venkataraman and Shanmugasundaram, 1992; Sinha *et al.*, 2002). However, performance is influenced by agro-climatic factors such as rainfall, temperature, and soil type. These findings highlight the value of site-specific bio-integrated nutrient management for enhancing sustainability and productivity in rice-based systems.

## Amelioration of FA toxicity by BGA

BGA has demonstrated the potential for admirable alleviation in soils contaminated with FA through the mitigation of both metal toxicity and improvement in the availability of nutrients. The fact that they fix nitrogen in the atmosphere and mobilize phosphorus makes them useful in enriching many substrates that are deficient in nutrients such as FA (Dwivedi *et al.*, 2000). *Anabaena doliolum* is unique in terms of its ability to bio-accumulate metals and enhance nitrogen and phosphorus content in FA (Rai *et al.*, 2000). Nevertheless, it is difficult to handle metal-contaminated algal biomass, which could have economic gains such as recovery of metals, e.g., Cu and Ni, through burning (Moffat, 1995). The application of sustained irrigation is necessary to keep the BGA alive in the field conditions, as they are photoautotrophs.

## Integrative pathway for sustainable algae-FA-rice system

Sustainable rice production embraces enhanced soil fertility, nutrient-use efficiency, and environmental safety without relying on chemical fertilizers. The integration of green algae and FA judiciously combines nutrient cycling with physicochemical soil improvements. FA contains essential macro- and micronutrients such as Si, Ca, Mg, K, Fe, and Zn, when added to soil at suable concentration, improves soil structure, porosity, and water-holding capacity, but reduces resistance (Subiksa *et al.*, 2026). An increase in soil pH due to the addition of FA reduces Al and Fe toxicity and enhances nutrient availability. Silicon supplemented through FA is beneficial for rice in providing mechanical strength to cell walls and increasing resistance to pests, diseases, and lodging. However, the presence of trace heavy metals in FA necessitates their limits to prevent ecological risks. Green algae (e.g., *Chlorella*, *Scenedesmus and Spirogyra*) play a significant role in stabilizing FA–amended rice soil by rapidly colonizing paddy soils along with irrigation water as biosorbents, immobilizing trace metals through cell wall binding, extracellular polysaccharide secretion (EPS), and intracellular sequestration. Ultimately, metal bioavailability is lessened, restricting their movement into the rice-based food chain. Algal EPS enhances aggregation in soil and the establishment of microhabitats of beneficial microbial communities. The FA-algae system is known to enhance the root architecture, nutrient and redox balance of the rice rhizosphere (Dwibedi *et al.*, 2008). The increased silicon and nutrient level enhances the ability of antioxidant defense mechanisms, decrease oxidative stress, and enhance photosynthetic rates. This leads to increased tillering and an increase in the biomass and grain yield of the rice plants (Chen *et al.*, 2024). The driving factors of FA and BGA application in paddy soil are illustrated in Fig. 1. In this schematic diagram, the application of BGA improving soil pH, texture and microbial activity has been depicted under controlled FA amendments. Green algae thus remediates heavy metals present in the FA that ultimately reduces the concentration of toxic heavy metals in the paddy soil, facilitating rice growth and yield.

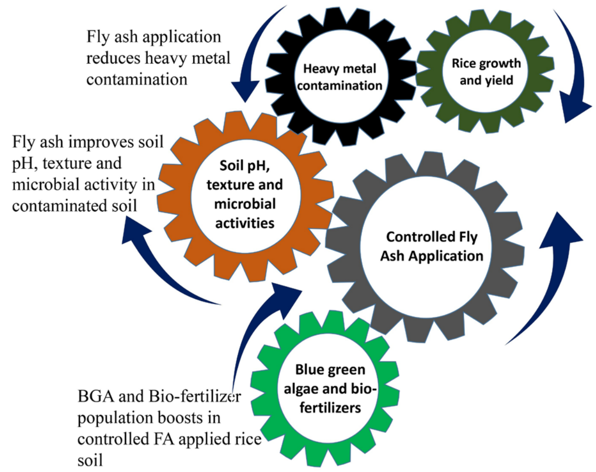


**Fig. 1:** Amelioration effect of fly ash on heavy metal contamination, enhancing soil properties, microbial dynamics, and rice growth and yield.

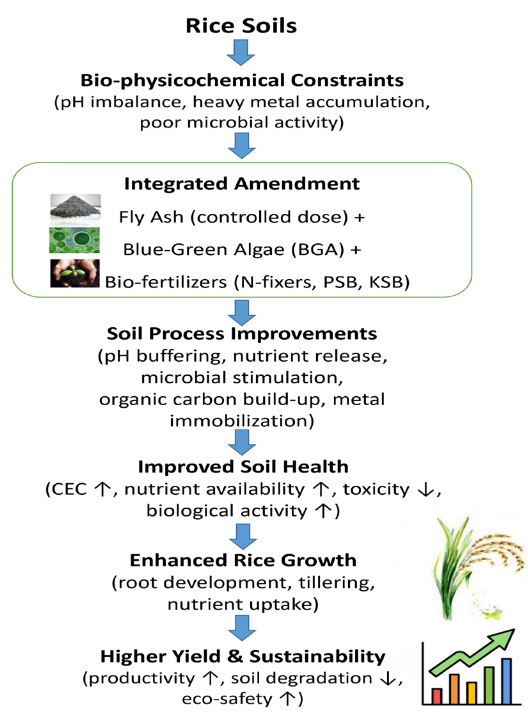


**Fig. 2:** Schematic diagram indicating synergistic effects of FA, BGA and Biofertilizers

**Table 1:** Effect of fly ash on metabolites, growth and yield of plants.

| *Sl. No.* | *Amendments* | *FA-Dose* | *Plant* | *Responses* | *References* |
|---|---|---|---|---|---|
| 1 | FA + alluvial Soil | 0–200 t/ha | Rice, wheat | Increased yield | Kumar *et al*., 2000 |
| 2 | FA + alluvial soil | 0–100 t/ha | Mustard, jute | Increased yield | Kumar *et al*., 2000 |
| 3 | FA + laterite soil | 0–200 t/ha | Rice, wheat | Increased yield | Kumar *et al*., 2000 |
| 4 | FA + laterite soil | 0–100 t/ha | Mustard, potato, lentil | Increased yield | Kumar *et al*., 2000 |
| 5 | FA + black soil | 0–50 t/ha | Sugarcane | Increased yield | Kumar *et al*., 2000 |
| 6 | FA + laterite soil | 0–150 t/ha | Groundnut | Increased yield | Kumar *et al*., 2000 |
| 7 | FA + laterite soil | 0–100 t/ha | Sugarcane | Increased yield | Kumar *et al*., 2000 |
| 8 | FA + black soil | 0–150 t/ha | Rice-green gram | Increased yield | Kumar *et al*., 2000 |
| 9 | FA + black soil | 0–120 t/ha | Cotton-rice | Increased yield | Kumar *et al*., 2000 |
| 10 | FA + laterite soil | 0–10 t/ha | Rice-groundnut | Increased grain yield by 26%, in combination with organic and inorganic sources. Better physical properties of soil reduce bulk density and enhance porosity and water holding capacity | Kumar *et al*., 2000 |
| 11 | FA + laterite soil | 0–20 t/ha | Rice-groundnut-mustard | Increased grain yields up to 15-18% | Kumar *et al*., 2000 |
| 12 | FA + laterite soil | 0–30 t/ha | Mustard-rice | Seed yield of 15-18% and an increased yield of rice by 13-15% | Kumar *et al*., 2000 |
| 13 | FA + laterite soil | 0–10 t/ha | Rice, groundnut, potato | Enhanced yield of rice by 14% and groundnut by 26% over control | Kumar *et al*., 2000 |
| 14 | FA + laterite soil (red) | 0–80 t/ha | Sunflower-groundnut | Increase in seed yield | Kumar *et al*., 2000 |
| 15 | FA + black soil | 0–80 t/ha | Sunflower-maize | Increased by about 25% in red soil | Kumar *et al*., 2000 |
| 16 | FA + alluvial soil | 0–650 t/ha | Tomato, cabbage, potato, wheat, pea -maize, wheat-maize | Increased grain yield | Kumar *et al*., 2000 |
| 17 | FA + alluvial soil | 0–650 t/ha | Sunflower, tomato, potato, wheat, berseem, red gram, maize, rice | Increased grain yield | Kumar *et al*., 2000 |
| 18 | FA + alluvial soil | 0–40/0–80 t/ha | Rice-wheat, cotton-wheat, Sunflower-maize, Wheat-rice | Increased grain yield | Kumar *et al*., 2000 |
| 19 | FA + alluvial soil | 100% ash body with 7.5 cm soil cover | Pigeon Pea,wheat | Increased grain yield | Kumar *et al*., 1999 |
| 20 | FA + black soil | 0–640 t/ha (residual effect) | Wheat-maize, Soybean-maize, lemon grass | Increased grain yield | Kumar *et al*., 1999 |
| 21 | FA + alluvial soil | 0–640 t/ha | Maize-onion, rice-sunflower | Increased grain yield | Kumar *et al*., 1999 |
| 22 | FA + laterite Soil | 0–240 t/ha | *Eucalyptus* | Increased grain yield | Kumar *et al*., 1999 |
| 23 | FA + laterite soil | 0–24% of pit volume | *Eucalyptus, Acacia auriculiformis, Casuarina equisetifolia, Acacia mangium* | Increased growth | Kumar *et al*., 2000 |
| 24 | FA + alkali- Saline eroded land (in arid zone) ash pond | 0–20% v/w | *Eucalyptus, Zizyphus, Jojoba* | Increased growth | Kumar *et al*., 2000 |

| *Sl. No.* | *Amendments* | *FA-Dose* | *Plant* | *Responses* | *References* |
|---|---|---|---|---|---|
| 25 | FA + laterite soil | 1/3 (W/V) | *Ceiba pentandra, Melia azadirach, Cassia siamea, Erythrina indica, Cassia glauca, Bauhinia purpurea, Pongamia glabra, Thevetia neriifolia* | Increased growth | Kumar *et al*., 1999 |
| 26 | FA + Usar | 0–5% | Rice, wheat | Increased growth | Kumar *et al*., 2000 |
| 27 | FA + Usar | 0–5% | Rice, mustard | Increased growth | Kumar *et al*., 2000 |
| 28 | FA + Usar | 0–5% | Rice, wheat | Increased growth | Kumar *et al*., 2000 |
| 29 | FA + Usar | 0–6% | Rice, wheat | Increased growth | Kumar *et al*., 1999 |
| 30 | FA + normal soil | 0.8–50% | Wheat (*Triticum vulgare*) (cv. Sonalika) | Increased germination growth, and yield | Singh *et al*., 1994 |
| 31 | FA + normal soil | @ 8% | Okra (*Abelmoschus esculentus*), Colocasia (*Colocasia esculenta*), potato, tomato | Beneficial in increasing the yield of vegetable crops | Sarkar, 2000 |
| 32 | FA + normal soil | 0.5–1% (w/v) | Corn and soybean | No influence on seed germination and seedling growth of the corn and soybean | Shukla and Mishra, 1986 |
| 33 | FA + normal soil | 4 g $g^{-1}$ $d^{-1}$ sprayed | *Dolichos lablab* | Loss in dry weight increases in leaf area and chlorophyll content | Dubey and Pawar, 1985 |
| 34 | FA + sandy | 2.12 and 30% | *Brassica parachinensis* and *B. chinensis* | Enhancement in germination enhances dry matter yield | Wong and Wong, 1989 |
| 35 | FA + compost | 100 kg/ha | Collard and muffured | Enhancing the dry matter yield assimilation of high levels of boron | Menon *et al*., 1993 |
| 36 | FA + normal soil | 100 kg/ha | *Helianthus annus* (Sunflower) | Oil yield increased, enhancing the growth and phytomass accumulation | Pandey *et al*., 1994 |
| 37 | FA + normal soil | 16–50% | *Dahlia pipinata* | Increases the tissue's dry weight | Kumar *et al*., 2000 |
| 38 | FA + normal soil | 200 t/ha | Rice boro | 40% increases in yield | Kumar *et al*., 2000 |
| 39 | FA + normal soil | 80 g/ha | Paddy | Enhanced paddy yield from 61.82 to 63.58 q/ha | Kumar *et al*., 2000 |
| 40 | FA + normal soil | 20 t/ha | Ground nut | yield increased | Kumar *et al*., 2000 |
| 41 | FA + normal soil | @ 25% | Brinjal | 50-60%more yield | Kumar *et al*., 1999 |
| 42 | FA + normal soil | @ 25% | Potato | 45% more yield | Kumar *et al*., 1999 |
| 43 | FA + normal soil | @ 25% | Cabbage | 29% more yield | Kumar *et al*., 2000 |
| 44 | FA + normal soil | 10 t/ha | Wheat | Increased wheat yield from 21.2 to 24.1 q/ha | Kumar *et al*., 1999 |
| 45 | FA + normal soil | 10 t/ha | Moong | increased the dry yield from 3.8 to 7.36 g | Kumar *et al*., 1999 |
| 46 | FA + normal soil | 2% (kg $m^2$ plot) | *Beta valgaris* | Better seedling growth and sugar production, whereas 4% and 8% were inhibitory | Singh *et al*., 1994 |
| 47 | FA + normal soil | 25–100% + PM | *Cassia siamea* and *Pisum sativam* | Accumulation of Zn, Cu, Ni and Fe boosts the productivity of agriculture and leguminous crops, antioxidant and metal detoxifying potential | Tripathi *et al.*, 2000; Kumar *et al*., 2002 |

Cont...

| Sl. No. | Amendments | FA-Dose | Plant | Responses | References |
|---|---|---|---|---|---|
| 48 | FA + normal soil | 0–8% | Rice and wheat | 2% to 4% (W/W) had beneficial effects on the dry matter, yield of paddy | Sikka and Kansal, 1993 |
| 49 | FA + normal soil | 25–100% | Chickpea | FA amended with soil exhibited high level of Glutahione GSH | Gupta *et al*., 2002 |
| 50 | FA + compost | 10–30% | *Albizia Procera* and *Acacia nilotica* | Increased free amino acid content leaves of both species at 10% FA concentration, exhibited higher value of chlorophylla, band total protein, proline, ascorbic acid, higher soluble sugar, high amount of starch, phenols | Tripathi and Tripathi, 1998 |

### Significance of other bio-fertilizers in FA-contaminated soils

Beneficial microorganisms like *Azotobacter*, *Azospirillum*, phosphorus-solubilizing bacteria (PSB), and potash-solubilizing bacteria (KSB) are used to remediate FA-contaminated soil, exploiting the nutrients and soil-enhancing properties of FA (pH, texture). Microbes can fix nitrogen and dissolve phosphorus to form a long-term way of increasing the amount of rice and reviving FA-mediated heavy metal contamination by complexing the heavy metals and enhancing the health of the soil (Jambhulkar, 2023). In one of the studies by Kumar *et al*., (2010), it was established that the use of FA as a carrier in the bio-fertilizer formulations was identified as a safe and effective approach to productive use of FA-contaminated soil. FA-based bacterial and algal biofertilizers were found to be able to increase the yield of wheat and rice, decrease further use of urea and SSP by 6-30%, and enhance soil organic carbon, nitrogen, and phosphorus, proving useful in sustainable crop production (Kaur and Goyal, 2014). The synergistic effects of FA, BGA and bio-fertilizers are depicted in Fig. 2, illustrating the bio-physicochemical constraints that transform with FA addition and BGA cultivation in water stagnated conditions, resulting in improved soil health and higher rice yield, and sustainability.

## Conclusion

The elemental toxicity arising from FA application is highly variable, depending on plant species, soil type, and FA characteristics. It was inferred that, except for Boron (B), the mineral elemental toxicity has been recorded; however, many investigations observed visible toxicity symptoms at higher concentrations of boron. *Brassica* species, string beans, and bell peppers showed poor growth and high B uptake under FA treatment. FA incorporation also altered nutrient dynamics, enhancing N, S, Ca, Na, and Fe while reducing P and Zn in rice. Researchers found minimal increases in trace metals with heavy FA applications to acidic soils and also reported no toxicity in some plants at moderate FA rates. However, cumulative uptake of Fe, Ni, and other metals in crop rotations signals the need for long-term monitoring. Beyond plant health, FA leachates significantly threaten groundwater quality. In this paper, the discussion was based on the overall use of FA that urgently requires regulation and safe disposal plans. More investigations are needed to streamline the application rate and tactics of various soils as well as various agro-climate zones to augment agronomic advantages and minimize environmental threats. There is an importance of research on metal speciation, bioavailability and translocation in the case of algae-mediated stabilization, and food security and environmental safety. Further omics-based metagenomics, transcriptomics, and metabolomics are to be examined with important microbial-algal-plant interactions and determine important functional pathways of nutrient cycling, stress tolerance, and detoxification. The bioavailability of certain green algal strains known to have high biosorption power, phytohormone production ability, or carbon capture capacity also needs specific screening and development. Although BGAs are not new bio-fertilizers in wetland rice technologies, the adverse application of BGAs in FA-contaminated sites has not been thoroughly investigated. Their long-term suitability in enhancing soil fertility and promoting sustainable vegetation on FA soils would require further research. A combination of FA-BGA with climatic resilient rice-farming, including water-saving irrigation and organic modification. The large-scale adoption needs to be assessed through life cycle analysis (LCA) and cost-benefit analysis to assess its economic viability and sustainability. The regulatory standards must also be enhanced to indicate the allowable level of heavy metals in FA applied to the agricultural land, and guidelines must be plainly stated with reference to the rate of use, application, and regulation of FA.

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## Conflict of interest

There is no conflict of interest between the authors.

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