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Sustainable Circular Economy: Transforming Fly Ash into Valuable Compost

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ABSTRACT

The increasing global concern over environmental sustainability has prompted a shift towards circular economy principles, aiming to minimize waste, promote resource efficiency, and foster a regenerative approach to production and consumption. This research explores the conversion of fly ash, obtained as a secondary product of coal combustion process, into valuable compost as a novel and eco-friendly solution within the circular economy framework. Fly ash, traditionally considered an industrial waste with potential environmental implications, can be repurposed into a valuable resource through innovative composting techniques. This study investigates the biological and chemical processes involved in the conversion of fly ash into nutrient-rich compost, highlighting the potential benefits in terms of waste reduction, resource recovery, and soil enrichment. The research employs a multidisciplinary approach, integrating principles of environmental science, microbiology, and engineering to optimize the composting process. Key factors such as microbial activity, nutrient cycling, and the influence of organic additives are examined to enhance the quality and effectiveness of the final compost product. Additionally, the study evaluates the potential of fly ash as compost is to improve soil fertility, sequester carbon, as well as mitigate environmental risks associated with traditional fly ash disposal. Through a life cycle assessment, the environmental impact of converting fly ash into compost is compared with conventional waste management practices, providing insights into the overall sustainability of the proposed circular economy solution. Economic feasibility and market potential are also explored, considering the commercial viability of large-scale fly ash composting operations.

Keywords: Environment; Fly ash; Compost; Circular economy.

1. INTRODUCTION

The principle of a sustainable circular economy involves minimizing waste land, promoting the continuous use of resources by designing products for longevity, reusing materials, and recycling to create a closed-loop system, reducing environmental impact. Fly ash, a byproduct of coal combustion, can be used as compost for crops due to its rich mineral content. It provides essential nutrients like potassium, calcium, and magnesium, promoting plant growth. Additionally, its alkaline nature can help neutralize acidic soil, improving soil fertility. Transforming fly ash into valuable compost aligns with circular economy principles by repurposing a waste product into a useful resource. This process not only diverts fly ash from traditional disposal methods but also contributes to a closed-loop system where materials are recycled and reused, reducing the overall environmental impact and promoting sustainable resource management.

In India, in the year 2021-2022, more than 197 coal or lignite based thermal power plants generated around 133 MTs of fly ash and it will surpass 1000 MTs during 2031-2032. Out of total fly ash generated, only 50% are utilised mainly in construction sector and remaining 50% proved to be hazardous for environment as it causes soil, water and air pollution. Fly ash consists of oxides of silica, alumina and iron as well as minor oxides of P, K, Ti, Ca, Na and Mg. These macro- and micronutrients proved beneficial for improving the texture of the soil and plant growth. Fly ash is used to ameliorate soil structure and reduce hydraulic conductivity and improve Water Holding Capacity (WHC) (Aitken *et al.* 1984).

To improve the texture and contents of trace elements, fly ash is used as an amendment for coarse-textured agricultural soils because of its silt texture and the presence of high amount of trace elements. Fly ash is used as a base to grow economically valuable flowers for floriculture purposes. Fly ash has been effectively utilized as a potent termiticide and herbicide for controlling insects and pests in paddy and various vegetable crops. It is also used as an efficient carrier material in different pesticide formulations, such as wettable powders, dusts, pellets, and herbal pesticides.

Fly ash is utilised for the remediation of soils contaminated by heavy metals because of several resemblance with soil and presence of essential micro-

nutrients (B, Cu, Zn, Fe, Co, Mn and Mo) and macro-nutrients (S, K, P, Ca and Mg). Due to lime and gypsum-like properties, fly ash is used in the reclamation of wastelands (mine spoil). As a carrier for nitrogen fixing as well as phosphate solubilizing bacteria such as *Azotobacter chroococcum*, *Azospirillum brasilense* and *Bacillus circulans* (Gaind *et al.* 2004) fly ash proved its positive effect on crop and health of soil (Kalra *et al.* 1997; Gaind *et al.* 2002) because of the properties like bulk density, WHC, aeration, insensitiveness to changes in moisture content of soil, cheaper cost and easy availability. Fly ash has good pH buffering quality and its granule size is 0.5-1.5 mm, which is ideal for carrier materials (Parab *et al.* 2015).

Fly ash is a potential replacement of agricultural lime which is a potent emitter of CO_2 (Chen *et al.* 2004; West *et al.* 2005). It thereby helps in reducing global warming by modifying the agriculture practices in an ecological way. This paper is a thorough analysis of various works done in recent times explaining the effect and utilisation of fly ash in agriculture sector and describing how different formulation of fly ash proved effective in crop growth and soil quality improvement.

In recent years, there has been a growing emphasis on sustainable practices, and one promising avenue is the transformation of fly ash into valuable compost. This review explores the potential of integrating fly ash into the circular economy, aiming to not only manage waste but also contribute to sustainable agriculture through compost production.

2. USES OF FLY ASH IN AGRICULTURAL SECTOR

2.1 Fly Ash as a Soil Ameliorant

One of the studies conducted to evaluate the effect of fly ash and micronutrient like zinc and iron on the yield of maize crop (*Zea mays*) by main Field Station, Agriculture department under Lovely Professional University of Phagwara which is in Punjab state of India. Fly ash was treated with recycling derived fertilizer, 12 % of each Zn-EDTA and Fe-EDTA and arranged in randomized block design. This treatment recorded the highest performance in maize yield attributes, with 1.73 cobs per plant, cob length of 18.17 cm, cob weight of 141.57 g, 339.86 grains per cob, cob girth of 14.03 cm, 13.26 grain rows per cob, and a 100-seed weight of 26 g. The seed yield reached 70.27 q/ha, indicating that this treatment produced the best overall response in maize productivity (Sarwan *et al.* 2019).

In another research, the effect of fly ash amended with blue green algae (BGA) and rhizobium inoculation on the growth and feasibility of legume species *Prosopis juliflora* L was analysed. There was a significant increase in biomass, chlorophyll a and b, protein content and *in vivo* nitrate reductase activity when fly ash is amended with BGA. Also, the accumulation of essential nutrients like iron, manganese, copper, zinc and chromium increased in fly ash amended with rhizobium. The study demonstrated that *P. juliflora* can be successfully grown on fly ash landfills, where it reduces metal concentrations through bioaccumulation, making it a suitable candidate for phytoremediation. Fly ash amended with BGA showed excellent results compared to other amendments with fly ash as it showed increase in chlorophyll a up to 20.11% and b up to 12.12%, total chlorophyll 16.34%, carotenoid level improved 43.21%, leaf 19.61% and root 70.28%. Protein increased slightly and improved nitrate reductase activity by 275.67% (Maiti *et al.* 2016).

A study demonstrated that fly ash inoculated with beneficial microorganisms, such as *Azotobacter chroococcum* and arbuscular mycorrhizal fungi, enhanced soil fertility, promoted plant growth, increased siderophore production, and stimulated the release of plant growth–promoting hormones (Parab *et al.* 2015). Experimentation on onion bulbs by applying 50 mg/ha dose of fly ash with 50% chemical fertilizer and azotobacter treatment improved the nutrient status of onion bulbs, yield and soil fertility. This treatment also improved the availability of Ca, Cu, Zn, Mn and Fe in soil (Parab *et al.* 2015). One more research showed that integrated nutrient treatment with fly ash at 10 mg/ha, organic waste and chemical fertilizers resulted in higher intake of N, P, K, Ca, Mg, Fe, Mn, Zn and Cu in paddy grains, which resulted in higher crop yield (Sarangi *et al.* 1997; Rautaray *et al.* 2003; Parab *et al.* 2015).

Fly ash also affects the physical properties of soil by increasing microporosity and WHC (Page *et al.* 1979; Ghodrati *et al.* 1995). Fly ash mixed with clayey soil noticeably reduced the bulk density and improved the soil structure. Hence, there was an improvement in porosity, root penetration, moisture retention and workability of the soil (Kene *et al.* 1991). At water scarcity areas, the improvement in WHC of soil is highly beneficial. Fly ash enhances the nutrition content of soil (Rautaray *et al.* 2003). Fly ash acts as liming agent and applied in acidic soil, thus improving the quality of soil and crop production (Matsi *et al.* 1999). Fly ash is a rich source of silica, which can enhance plant-available silicon in soil and increase silicon uptake in rice, thereby promoting its growth (Lee *et al.* 2006). Fly ash is highly recommended to be utilized in agriculture field because of its composition of potassium, calcium, magnesium, sulphur and phosphorous (Kalra *et al.* 1997). An experiment demonstrated that sorghum (*Sorghum bicolor*), alfalfa, carrots (*Daucus carota*), beans (*Phaseolus vulgaris*), and tomatoes (*Solanum lycopersicum*) could be successfully grown on acidic soil (pH 6.0) amended with 125 t/ha of unweathered fly ash. Stoewsand *et al.* (1978) demonstrated that winter wheat (*Triticum aestivum*) produced Se-rich grains when grown

on a field containing fly ash. According to Khan *et al.* (1997), fly ash at approximately 14% was found to exhibit nematicidal activity and was effective in managing root-knot disease caused by *Meloidogyne* spp., commonly affecting tomato crops (Kishor *et al.* 2009).

Another work showed that the growth and yield of chick pea were found to be increased under the application of fly ash along with TPP wastewater and uniform dose of NPK fertilizer. Four different amendments of fly ash were prepared (0%, 10%, 20% and 40%) and it was found that fly ash (10%) showed better results compared to fly ash (0%) but fly ash (20% and 40%) proved to be harmful for chick pea (Irfan *et al.* 2017).

A study conducted in Punjab over five years (2006–2011) across 20 villages evaluated the effects of fly ash-based biofertilizers, Nitrofix and Phosul, on wheat, and fly ash combined with blue-green algae on rice. The results showed a significant increase in crop yields, with paddy yield improving by 5–23 quintals and wheat yield by 2–20 quintals over the study period. Additionally, soil properties improved, with soil organic carbon increasing by 0.10–0.51%, total nitrogen by 0.001–0.008%, and phosphorus by 5–26 mg/kg. Furthermore, several tree species, including *Dalbergia sissoo* (Indian rosewood), *Albizia lebbeck* (siris), *Eucalyptus tereticornis* (forest red gum), *Acacia auriculiformis* (auri), *Populus deltoides* (eastern cottonwood), and *Acacia nilotica* (babul), as well as aromatic and flowering plants such as marigold, lemongrass, gladiolus, and *Lilium*, were successfully grown on fly ash–amended wastelands. These applications also resulted in reduced adverse effects and enhanced biomass production.

One of the studies conducted at China proved that fly ash amended with mine soil at 1% and 5% application rates enhances plant growth and soil fertility (Kaur *et al.* 2014).

A study conducted in the north-eastern zone of Tamil Nadu, India, evaluated the effects of fly ash on the growth parameters, nutrient uptake, yield of sesame, and soil fertility in groundnut and sesame crops. The fly ash obtained from Neyveli Lignite Corporation was found to contain higher amounts of Ca, Mg, S, and Si, and lower amounts of P, K, and B. Application of fly ash at 40 t/ha resulted in significant improvements in growth parameters, yield attributes, nutrient uptake, and seed yield in both groundnut and sesame crops (Baskar *et al.* 2017).

Fly ash + ordinary garden soil (in the ratio of 10:90) + diluted distillery effluent was applied to the pot culture of marigold plant to observe its effect on the vegetative growth and photosynthetic pigment like chlorophyll a and b. A remarkable increase in vegetative growth was observed, including enhanced branching, larger flower size, greater leaf area, and an increased number of nodes. Additionally, total chlorophyll, carotenoids, and ascorbic acid contents increased significantly (Kumari *et al.* 2012).

In one study conducted to determine the effect of different concentrations of fly ash, with or without PGPR (plant growth–promoting rhizobia such as *Azospirillum* and *P. striata*), on soil pH and phosphorus availability in acidic soil, a total of 13 treatments were carried out. Among these, the treatment consisting of a higher amount of fly ash combined with PGPR and *P. striata* showed an increase in phosphorus levels. Laboratory incubation studies further revealed that, after 90 days of incubation, soil pH increased from acidic to neutral, while no significant changes in pH were observed at 10, 20, and 30 days after incubation. Additionally, fly ash @ 80 t/ha and fly ash @ 80 t/ha + *P. striata* showed positive effects on available phosphorus in the soil. The latter treatment also exhibited a decreased phosphorus fixation capacity (control = RDF + FYM).

Lime is commonly added to soil as an ameliorant to increase the pH of acidic soils. However, the carbon present in lime contributes to global warming by releasing carbon dioxide into the atmosphere, as reported by the Intergovernmental Panel on Climate Change. Therefore, to minimize global warming, fly ash can be used as an alternative soil ameliorant in place of lime. One experiment also showed that 1 ton of fly ash sequestered about 26 kg of CO_2 (West *et al.* 2005).

2.2 Fly ash as a Carrier Material for Developing Biofertilizers

To investigate the role of fly ash as a carrier material for two plant growth–promoting bacterial strains on the growth and yield of eggplant (*Solanum melongena*), a field trial was conducted. *Burkholderia* sp. L2 and *Bacillus* sp. A30 were inoculated with biochar derived from agricultural waste and fly ash obtained from a coal-based thermal power plant, and applied to the eggplant field. The results showed that seed germination was highest compared to treatments with chemical fertilizers or conventional biofertilizers. Furthermore, the combination of *Burkholderia* sp. L2 + biochar + fly ash resulted in the maximum fruit yield, along with improved soil water-holding capacity, moisture content, and dehydrogenase activity (Tripti *et al.* 2022).

When fly ash was inoculated with *Azotobacter chroococcum* and vermicompost and applied to maize, a significant improvement in crop growth was observed. Seed germination increased markedly, while chlorophyll

content, carotene content, and net assimilation rate increased by 13%, 3%, and 10%, respectively.

The soil microbial population is also maintained through bioformulations of fly ash inoculated with *Azotobacter* and *Azospirillum* strains isolated from the wheat rhizosphere. This fly ash-based bioformulation (300 mesh) was applied to wheat seeds, resulting in enhanced seed germination, increased plant height, improved biomass accumulation, and higher crop yield (Kumar *et al.* 2010).

A study conducted in Sri Lanka aimed to develop a cost-effective carrier material for biofertilizers to enhance the solubility of Eppawala rock phosphate, a rich source of plant-available phosphorus that improves soil fertility. The results showed that the treatment comprising B1 bacterial strain (a potential phosphate solubilizer identified on PVK agar medium), rock phosphate (40 g), *Gliricidia sepium* (10 g), kaolin clay (30 g), and fly ash (20 g) exhibited significantly higher performance ($p < 0.05$). Fly ash acted as a nutrient-enriched carrier material and enhanced the phosphorus-solubilizing activity of the bacteria, thereby improving the solubilization of phosphorus from high-grade Eppawala rock phosphate (HERP).

2.3 Fly ash as Amendment for Making Biofertilizers

Fly ash is mixed with vermicompost to prepare a blended bio-fertilizer having chemical composition exactly close to chemical fertilizers with N:P:K ratio of 4:6:4. Such blended bio-fertilizers are sustainable and eco-friendly.

As ornamental plant industry and floriculture trend is gaining popularity day by day, it may be beneficial to utilise fly ash in such industries as liming agent to increase the pH of the substrate used for floriculture. The substrate comprised sphagnum peat, pine bark, coir dust, and either perlite or vermiculite, and its pH may decrease to around 4. To raise the pH, dolomite or calcitic limestone was added (Chen *et al.* 2004). To limit their uses fly ash can be incorporated as liming agent for increasing pH of substrate. Fly ash is available in large quantity as a coal industry waste so it can be used in floriculture and ornamental plant industries and benefit the growing floriculture industry (Pandey *et al.* 2009).

In one study, rice was grown under different treatments involving fly ash (FA10 and FA100, applied at 10 and 100 t/ha, respectively), garden soil, nitrogen fertilizer (NF90 and NF120, applied at 90 and 120 kg/ha, respectively), and blue-green algae (BGA12.5 at 12.5 kg/ha). The results showed an excellent response in terms of crop yield and plant growth, along with reduced nitrogen fertilizer requirement, particularly in the treatment combining FA10 + NF90 + BGA12.5 (Tripathi *et al.* 2008).

Department of Microbiology, Faculty of Agriculture, Annamalai University conducted one pot culture experiment to study the effect of lignite fly ash obtained from Neyveli Lignite Corporation along with bio-fertilizer *Azospirillum* and *Phosphobacteria* on the growth and yield of Bhendi (*Abelmoschus esculentus* L.). Mixing *Azospirillum*, *Phosphobacteria* and lignite fly ash @ 40 t/ha proved highly effective in increasing plant height by 47.10 cm, root length by 21.63 cm, increase of flowers (31.66 per plant), increase of fruits (29.66 per plant) and fruit yield (92.43 g/plant) (Sriman *et al.* 2020).

Another study conducted in Sri Ganganagar District, Rajasthan, during the Rabi season evaluated the effect of fly ash amendment on the concentration of photosynthetic pigments in wheat (*Triticum aestivum*). The fly ash used in the study was obtained from the Suratgarh thermal power plant, Sri Ganganagar, Rajasthan. Different amendment of fly ash with soil was prepared and applied to the wheat field. Treatment of 12% fly ash with soil showed increased chlorophyll-a by 0.239 µ/gm and total chlorophyll by 0.430 µ/gm. Treatment made of 8% fly ash + soil showed marginal enhancement in the concentration of chlorophyll-b by 0.045 µ/gm in the wheat crop (Verma *et al.* 2017).

The role of fly ash as an amendment, when combined with inorganic materials in soil, has shown beneficial effects. When mixed with lime, fly ash helps alleviate Al and Mn toxicities in the soil. In combination with gypsum, it enhances soil water infiltration. Furthermore, the combined application of fly ash, gypsum, and lime improves soil pH, enhances soil structure, promotes the growth of soil microorganisms, and helps maintain calcium balance in the soil (Ram *et al.* 2014).

In one more experiment, fly ash was amended with soil at 0, 0.5, 1.0, 2.0, 4.0, 8.0 and 10.0 kg/m^2 and with N_2 fixing cyano-bacteria masses to find out the effect in rice crop. These amendments proved highly beneficial in the growth of paddy and increased in the yield of the crop up to 8.0 kg/m^2. Fly ash + soil amended at 10.0 kg/m^2 enhanced the activities of different enzymes present in leaves. Fly ash + soil amended at 4.0 kg/m^2 enhanced protein composition of rice grains to the elevated level. Fly ash + soil at 4.0 kg/m^2 amended with cyano-bacteria showed maximum grain weight of rice crop. Fly ash at 1.0 kg/m^2 and 4.0 kg/m^2 amended with soil along with cyano-bacteria recharged the soil of essential micronutrient and also lessened the toxic metal loads in the soil (Padhy *et al.* 2016).

2.4 Fly Ash as Inoculant

A demonstration of effect of blue green algae inoculated with fly ash on the production of paddy crops took place in the Department of Biotechnology, Thapar University, Patiala, Punjab. In this study, seven filamentous heterocystic region specific BGA were isolated from rhizospheric zone of paddy (rice) crop field soil and from the pond of fly ash disposal. The BGA used include *Calothrix* sp., *Anabaena flos-aquae*, *Desmonostoc* sp. DGRKC, *Nostoc commune*, *Nostoc* sp. PS1, *Nostoc* sp. DGRKF, and *Anabaena* sp. It was found that fly ash-based inoculation with BGA showed remarkable increase of 6 qtl/ha of Basmati1401, 4 qtl/ha of PUSA 1121, 3 qtl/ha of PR118 and Shabnam rice varieties. All these seven BGA were incorporated with different treatment made of fly ash (100%), soil (100%), montmorillonite (100%), fly ash + soil (50-50%), fly ash + montmorillonite (50-50%) and applied to PUSA 1121 cultivation and examined by pot experiment. It was observed that fly ash + soil (50-50%) + seven BGA inoculants showed enhanced yield of grains, increase in organic carbon, increase in phosphorous content and total nitrogen content to 14.3 g/pot, 0.43%, 17 mg/kg and 0.168%, respectively (Kaur *et al.* 2014).

3. DISCUSSION

The sustainable circular economy concept aims to reduce waste and promote recycling and reuse. Transforming fly ash into valuable compost aligns with this goal by utilizing a waste product (fly ash) to create a valuable resource (compost). The discussion of this review work focus on several key points:

- **Nutrient Enrichment:** Fly ash, though considered a waste product from coal combustion, contains minerals like calcium, magnesium, and potassium that can enrich compost, providing essential nutrients for plant growth.
- **Soil Amendment:** Composting fly ash can improve soil structure, aeration, and water retention, making it beneficial for soil health and plant growth.
- Heavy Metal Immobilization: Fly ash composting can help immobilize heavy metals present in fly ash, reducing their bioavailability and potential negative impact on the environment.
- **Waste Management:** Converting fly ash into compost reduces the amount of waste sent to landfills, contributing to waste management and reducing environmental pollution.
- **Cost-effective:** Using fly ash for composting can be a cost-effective way to utilize a waste product and create a valuable resource for agriculture.

However, it's important to note that the effectiveness of transforming fly ash into compost can vary depending on the specific constitution of the fly ash, the composting process used, and the intended use of the compost. Proper testing and monitoring are necessary to ensure that the resulting compost meets regulatory standards and is safe for use.

4. CONCLUSION

In conclusion, the review demonstrates the potential of transforming fly ash into valuable compost as a sustainable circular economy solution. This innovative approach not only addresses the environmental challenges associated with fly ash disposal but also contributes to the creation of a valuable resource for agriculture. Implementing such practices can foster a rational and sustainable approach for management of the waste, promoting environmental stewardship and resource efficiency. An analysis of various studies on the effective use of fly ash from coal-based thermal power plants in the agricultural sector indicates its potential as a carrier material for nitrogen-fixing bacteria, a soil amendment for improving fertility and crop yield, a pesticide and insecticide, and a liming agent in floriculture. Fly ash proved to be highly beneficial and this approach of using fly ash for different purposes in supporting the bio-fertilizer industry is highly commendable and can solve the serious issues of fly ash disposal in an economical as well as ecological way.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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