Review Article

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Sustainable Circular Economy: Transforming Fly Ash into Valuable Compost

Vandana Jangde[1*] Shweta Choubey[2] and Danuj Kumar Markam[1]
[1]Department of Chemistry, Jhada Sirha Government Engineering College, Jagdalpur, Bastar, CG, India
[2]Department of Basic Science and Humanities, Government Engineering College, Raipur, CG, India
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*vandanajangde4@gmail.com

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 is 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. The findings of this research contribute to the growing body of knowledge on circular economy practices by presenting a sustainable and economically viable alternative for managing fly ash waste. The outcomes may inform policymakers, industries, and environmental practitioners in developing strategies to transition towards more circular and environmentally responsible waste management practices. Ultimately, this research aims to promote the integration of fly ash composting into circular economy models, fostering a greener and more sustainable future.

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 the creation of a closed-loop system where materials are recycled and reused, reducing the overall environmental impact and promoting sustainable resource management.

In India in 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 until year 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 which is a concern for worry. 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 as ameliorate to soil structure and reduce hydraulic conductivity and improve 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 it consists of high amount of trace elements. Fly ash is used as a base to grow economically valuable flowers for floriculture purposes. As a potent termiticide and herbicide have been developed from fly ash incorporation against insect and pests of paddy and many vegetables where fly ash is utilised as insecticide and incorporated as effective carrier in many formulations of insecticides (wet-table powder, dust, and 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) because of its proved +ve 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, easy availability. Fly ash has good pH buffering quality and its size of the granules is 0.5-1.5 mm which is ideal for carrier material (Parab *et al.* 2015).

As 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. Fly ash is used in many forms in improving the crop yield and replacing the chemical fertilizers and becoming a boon in the field of agriculture.

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. THERE ARE MANY METHODS AND WAYS IN WHICH FLY ASH CAN BE UTILISED IN AGRICULTURE SECTOR AS DISCUSSED BELOW

2.1 Fly Ash as Soil Ameliorate

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 percent of Zn EDTA and same percentage of Fe EDTA was arranged in randomized block design. It was recorded that this treatment shows maximum reports of cobs per plant (1.73), length of cobs increased up to 18.17 cm, cob weight gained around 141.57 g, grains rows/cob increased to 339.86, cob girth (14.03 cm), grain rows per cob (13.26), weight of 100 seeds (26 g) and yield of the seeds increased to 70.27 q/ha. This treatment showed best response on the yield of maize crop (Sarwan *et al.* 2019).

In another research the effect of flyash ameliorated with blue green algae, Rhizobium inoculation on the growth and feasibility of legume species Prosopis Juliflora L was analysed. There is 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 research showed that P. Juliflora is grown in fly ash landfills and it reduces the metal content of fly ash by bio-accumulation and is beneficial for phytoremediation purposes. 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%. So both the amendment of fly ash helped in improving the production of crops as well as decontamination of landfills dumped with fly ash by the using P. Juliflora (Maiti *et al.* 2016).

A demonstration of effect of fly ash inoculated with beneficial microorganisms like Azotobacter Chroococcum and Arbuscular Mycorrhizal Fungi helped in upgrading of soil fertility, plant growth, siderophore production and 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 10mg/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 results in higher crop yield (Sarangi *et al.* 1997; Rautaray *et al.* 2003; Parab *et al.* 2015).

Fly ash also affect the physical properties of soil by increasing microporosity and water holding capacity (Page *et al.* 1979; Ghodrati *et al.* 1995). Fly ash mixed with clayey soil noticeably reduced the bulk density and soil structure is also improved and hence there is improvement in porosity, root penetration, moisture retention and workability of the soil (Kene *et al.* 1991). At water scarcity areas the improvement in water holding capacity 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 quality of soil and increasing crop production (Matsi *et al.* 1999). Fly ash is a rich source of many elements like Silicon which enhance the Silicon content in rice crop and enhance 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 that sorghum (Sorghum Bicolor), alfalfa, carrots (Daucus Carota), beans (Phaseolus Vulgaris), tomatoes (solanum lycopersicum) etc could be easily grown on acidic soil (pH 6.0) and treated with 125 mt/ha of un-weathered fly ash. Stoewsand *et al.* (1978) demonstrated that winter wheat (Triticum Aestivum) produced Selenium rich grains when grown on a field containing fly ash. According to Khan *et al.* (1997) the level of fly ash around 14 percent was found to have nematicidal effect and is suitable for treatment of root knot disease caused by Meloidogyne sp, commonly occurring in tomato crop (Kishor *et al.* 2009).

Research done by Irfan Ahmad et al on Cicer Arientinum L (Chick Pea) showed that 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 are prepared i.e 0%, 10%, 20% and 40% and it was found that fly ash (10%) showed better results compared to fly ash (0%) but flyash (20% and 40%) proved to be harmful for chick pea (Irfan *et al.* 2017).

In Punjab a study was conducted continuously for 5 years from 2006 to 2011 in total 20 villages and observed the effect of nitrofix and phosul which are fly ash based bio-fertilizers on wheat and fly ash with blue green algae bio-fertilizer on rice and obtained a significant yield of paddy crops increases to 5 to 23 quintals and yield of wheat increases from 2 to 20 quintals within 5 years of time span, also soil organic carbon, total nitrogen and phosphorous improved 0.10-0.51%, 0.001-0.008% and 5-26 mg/kg respectively in the soil. Many wild trees species like Dalbergia Sisso (Indian rosewood), Albizzia Lebbek (siris), Eucalyptus Tereticornis (forest red gum), Acacia Auriculiformis (auri), Populus Deltoides (eastern cottonwood), Acacia Nilotica (babul) and few aromatic flowering plants like marigold, lemon grass, gladioli and lilium have grown effectively on wastelands amended with fly ash and also observed a decline in adverse effects and increase in 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 also improved many folds (Kaur *et al.* 2014).

Research conducted on the effect of groundnut and sesame on the growth parameter, uptake of nutrient, yield of sesame, soil fertility in North-eastern zone of Tamil Nadu, India. It was found that fly ash obtained from Nayveli Lignite Corporation consists of higher amount of Ca, Mg, S and Si and lesser amount of P, K, and B. Fly ash @ 40t/ha is applied and caused a significant improvement in the yield attributes, growth parameters, seed production of both groundnut and sesame crops (Baskar *et al.* 2017).

Fly ash + ordinary garden soil (in the ratio of 10:90) + diluted distillery effluent is 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 growth in the vegetative parts like branches, flower size, leaf area, increased in number of nodes was seen and total chlorophyll, carotenoids and ascorbic acid also increased drastically. This work showed how “Pollutant turns Nutrients, hence proved the concept of “Waste to Health” (Kumari *et al.* 2012).

In one of the study conducted to find out the effect of different concentration of fly ash with or without using PGPR (Plant Growth Promoting Rhizobium like Azospirillum and P. Straita) on level of pH and phosphorous availability of acidic soil. Total 13 treatments were prepared out of which the treatment made up of mixing higher amount of fly ash with PGPR and P.Strata showed elevation in the level of phosphorus. Also, the laboratory incubation studies showed that after 90 days of incubation period there is increase in the pH of soil from acidic to neutral and there is no significant effect on the pH level at 10, 20 and 30 days after incubation. Also the treatments number 9(fly ash @ 80t/ha) as well as treatment number 13(fly ash @80t/ha + P. Strata) showed positive results in the level of available P in the soil. Treatment 13 showed decreased Phosphorus fixation capacity compared to treatment 1 (control= RDF + FYM).

Lime is added to the soil as ameliorate to increase the pH of acidic soil but the C in lime is contributing drastically in global warming by releasing carbon dioxide to the atmosphere assumed by Intergovernmental Panel on Climate Change. So as to minimise the global warming, fly ash is used as soil ameliorate 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 Flyash as a Carrier Material for Developing Biofertilizers

For investigating the role of Fly ash as carrier material for two Plant Growth Promoting bacterial strain on the growth and production of eggplant (solanum melongena) a field trial is conducted. Burkholderiasp.L2 and Bacillus sp. A30 were mixed (inoculated) with biochar obtained from agricultural waste and fly ash from coal based TPP and are subjected directly to the field of eggplant. It was observed that seed germination is maximum compared to application of chemical-based fertilizers or normal bio-fertilizers. A combination of Burkholderiasp.L2 + bio-char + fly ash gives maximum fruit yield percentage and enhanced water holding capacity, moisture content of soil and dehydrogenase activity (Tripti *et al.* 2022).

When fly ash is inoculated with Azotobacter Chroococcum and vermicompost and subjected to observe the growth of maize crop. It was found that percentage germination of seed increases tremendously and percentage of chlorophyll, carotene and Nominal Rate of Assistance increases 13%, 3% and 10% respectively.

Microbial population in soil is also maintained by bio-formulation of fly ash with Azotobacter and Azospirillum strains segregated from wheat rhizosphere. This bio-formulation in fly ash of 300 meshes is applied to the wheat seeds for enhancing germination of seeds, improved in the plant height, biomass is increased efficiently as well as crop yield (Kumar *et al.* 2010).

In Sri Lanka research was conducted to produce a cost-effective carrier material for bio-fertilizers to improve the solubility of Eppawala Phosphate because it provides high amount of plant nutrient phosphorous and has ability to improve soil fertility. It was found that high performance was shown by treatment prepared by mixing B1 bacterial type (potential phosphate solubilizer on PVK agar medium) + Rock Phosphate (40 g) + Gliricidia Sepium (10 g) + Kaolin Clay (30 g) + fly ash (20 g) with $p<0.05$. Fly ash proved to be nutrient enriched carrier material and hence enhance the phosphorous solubilizing activity of bacteria for solubilizing phosphorous in HERP (High Grade Eppawala Rock Phosphate).

2.3 Flyash as Amendment for Making Biofertilizers

Flyash 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-fertilizer are sustainable and environmental friendly technology.

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 comprises of sphagnum peat + pine bark + coir dust + perlite or vermiculite (Chen *et al.* 2004) and pH falls down to 4 so as to increase pH dolomite and calcitic limestone are used. 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 Industries (Pandey *et al.* 2009).

In one of the research rice is gown under different treatment of fly ash i.e, FA10 and FA100 according to the application of fly ash at 10 ton per hectare and 100 ton per hectare, respectively + normal soil from garden with nitrogen fertilizer application i.e, NF90 and NF120 according to the application of NF at 90 kg/ha and 120 kg/ha respectively + BGA12.5 application at 12.5 kg/ha. Excellent response was recorded in the yield of crop and growth of plant and reduction in utilisation of nitrogen fertilizer when FA10 + NF90 + BGA12.5 were applied to the crop (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 Nayveli Lignite Corporation along with bio-fertilizer Azospirillum and Phosphobacteria on the growth and yield of Bhendi (Abelmoschus Esculentus L.). A treatment was made by mixing Azospirillum + Phosphobacteria + Lignite fly ash @ 40 t/ha and applied to Bhendi crop. This treatment proved highly effective in increasing plant height by 47.10 cm, root length by 21.63 cm, increase of 31.66 flowers per plant, increase of 29.66 fruits per plant and fruit yield increased to 92.43 gm/plant (Sriman *et al.* 2020).

In another study conducted at Sri Ganganagar District, Rajasthan during Rabi season to find out the effect of amendment of fly ash with soil on the concentration of pigments necessary for photosynthesis in wheat plant (Triticum Aestivum). Fly ash was obtained from Suratgarh TPP, Sri Ganganagar, Rajasthan. Different amendment of fly ash with soil is prepared and applied to the wheat field. Treatment of 12% fly ash with soil showed increased in the concentration of 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).

Role of fly ash as amendment with inorganic materials present in soil showed that when fly ash is mixed with lime then it removes the Al and Mn toxicities from soil. And when fly ash is mixed with gypsum then it increases the water infiltration of the soil. Combination of fly ash + gypsum + lime showed correction in soil pH, soil structure, improvement in the growth of soil microorganisms and Ca balance in soil also showed improvements (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 is ameliorated 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 upto 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 ameliorate with cyano-bacteria showed maximum 1000 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 BGA which are filamentous heterocystic region specific were separated from rhizospheric zone of paddy (rice) crop field soil and from the pond of fly ash disposal. These BGA are Calothrix sp., Anabaena flos-aquae, Desmonostoc specie DGRKC, Nostoc commune, Nostoc species PS1, Nostoc species DGRKF and Anabaena species. 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 enhance 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. RESULTS AND 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 results and 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.

Overall, the results and discussion of research on transforming fly ash into valuable compost would likely highlight the potential of this approach to contribute to a more sustainable circular economy by reducing waste, conserving resources, and promoting environmental and economic benefits.

4. CONCLUSION

In conclusion, the research 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. After analysing different works done on the effective deployment of fly ash obtained from Coal Based TPP in Agriculture Sector as carrier material for nitrogen fixing bacteria, as amendment for improving soil fertility and crop yield, as pesticide and insecticide and as liming agent for floriculture sector. 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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