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Green Chemistry–Based Sustainable Valorization of Fly Ash into Bio-Organic Composite Materials

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Abstract: *The continuous production of fly ash from coal-based thermal power plants has emerged as a significant environmental concern due to challenges associated with its disposal and long-term ecological impact. The present research focuses on a green chemistry-oriented strategy for the sustainable utilization of fly ash through the development of bio-organic composite materials. Fly ash collected from Chandrapur Super Thermal Power Station (CSTPS), Chandrapur, Maharashtra, India, was incorporated into biodegradable matrices composed of starch, cellulose derivatives, and lignin-based resin. The composites were fabricated under ambient, solvent-free conditions, ensuring minimal energy consumption and environmental impact. Detailed characterization was carried out to evaluate density, porosity, compressive strength, and thermal stability using thermogravimetric analysis (TGA). The results reveal that optimized fly ash incorporation enhances mechanical performance and thermal resistance while maintaining environmental safety. This study demonstrates that fly ash can be effectively converted into value-added, eco-friendly materials, supporting sustainable development and green chemistry principles.*

Keywords: Fly ash; Bio-organic binders; Green chemistry; Sustainable composites; Thermogravimetric analysis

I. INTRODUCTION

Coal-based thermal power plants generate large quantities of fly ash as a by-product of coal combustion. Fly ash primarily consists of silica, alumina, calcium oxide, and iron oxides, and its uncontrolled disposal can lead to serious environmental problems such as air pollution, soil degradation, and groundwater contamination [2–4]. Conventional disposal practices, including ash ponds and landfilling, are increasingly unsustainable due to land scarcity and long-term ecological risks.

Green chemistry provides an effective framework for addressing these challenges by promoting the design of safer materials, energy-efficient processes, and waste minimization [1,8]. In recent years, increasing emphasis has been placed on the utilization of industrial waste materials in

combination with biodegradable and renewable binders [5–7]. The incorporation of fly ash into bio-organic matrices offers a promising route for waste valorization while reducing dependence on synthetic polymers.

The present study aims to develop fly ash-based bio-organic composite materials using natural binders and to systematically investigate their physical, mechanical, thermal, and environmental properties.

II. OBJECTIVES OF THE STUDY

The objectives of the present work are:

- To utilize fly ash as a functional filler in bio-organic composite systems
- To employ biodegradable binders such as starch, cellulose derivatives, and lignin-based resin
- To evaluate density, porosity, and compressive strength of the composites
- To assess thermal stability using thermogravimetric analysis

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- To examine the environmental safety and sustainability of the developed materials

III. GREEN CHEMISTRY PERSPECTIVE

The present research aligns with key principles of green chemistry, including waste prevention through productive fly ash utilization, use of non-toxic and biodegradable binders, energy-efficient processing under ambient conditions, and reliance on renewable feedstocks [1,8]. The developed composites represent a sustainable approach to industrial waste management and material development.

IV. MATERIALS AND METHODS

4.1 Materials

Fly ash was collected from Chandrapur Super Thermal Power Station (CSTPS), Chandrapur, Maharashtra, India, one of the major coal-based power plants in central India [9]. The fly ash was light grey in color and fine in texture.
The bio-organic binders used were:
Starch, serving as a natural binding and film-forming agent
Cellulose derivatives, providing mechanical reinforcement and structural integrity
Lignin-based resin, contributing rigidity and improved thermal resistance
Distilled water was used as a green processing medium.

4.2 Pre-Treatment of Fly Ash

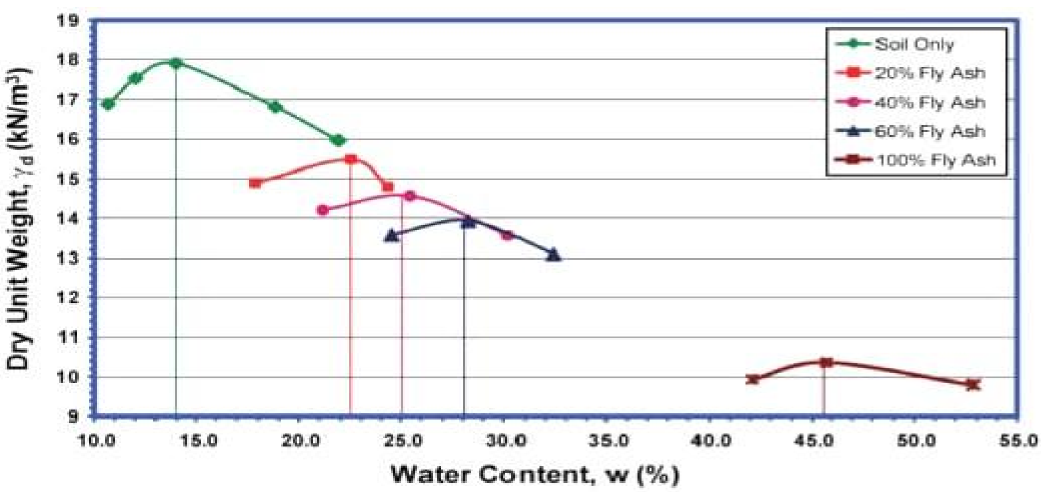
The collected fly ash was air-dried at room temperature to remove moisture and sieved to obtain uniform particle size. No chemical or thermal activation was applied, ensuring low energy consumption and environmental safety [11].

4.3 Preparation of Bio-Organic Composites

Fly ash was incorporated into the binder matrix at 10, 20, 30, 40, and 50 wt%. The binders were dispersed in distilled water under mechanical stirring, followed by gradual addition of fly ash to ensure homogeneous mixing. The slurry was cast into molds and cured at ambient conditions without external pressure or heat.

V. RESULTS AND DISCUSSION

5.1 Density Analysis



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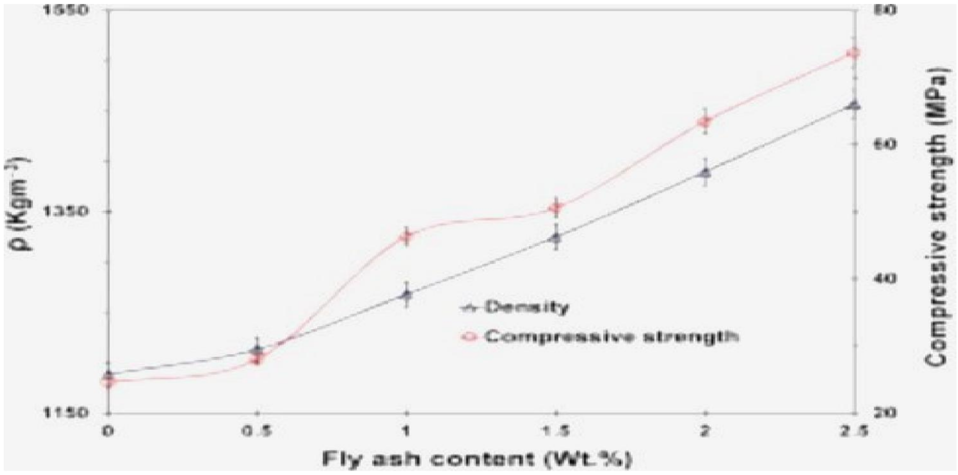
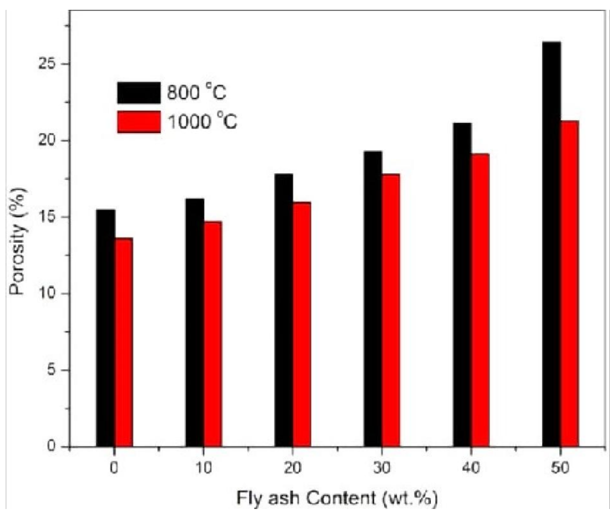


The density of the composites increased steadily with increasing fly ash content up to 40 wt%, indicating improved particle packing and reduced internal voids. The fine particle size of fly ash enabled effective pore filling within the bio-organic matrix, leading to enhanced compactness. At 50 wt% fly ash, a slight reduction in density was observed, likely due to particle agglomeration and limited binder availability.

This behavior suggests that 40 wt% fly ash represents the optimum composition for achieving maximum densification, in agreement with previous studies [15,16].

5.2 Porosity Analysis



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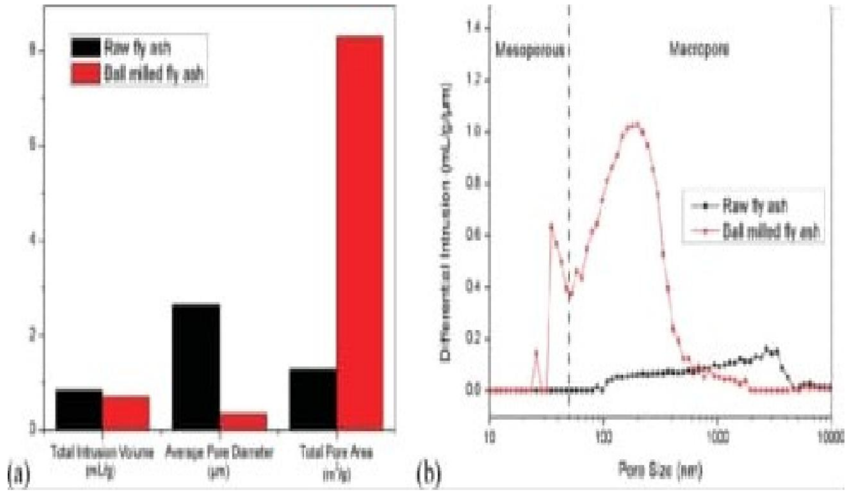

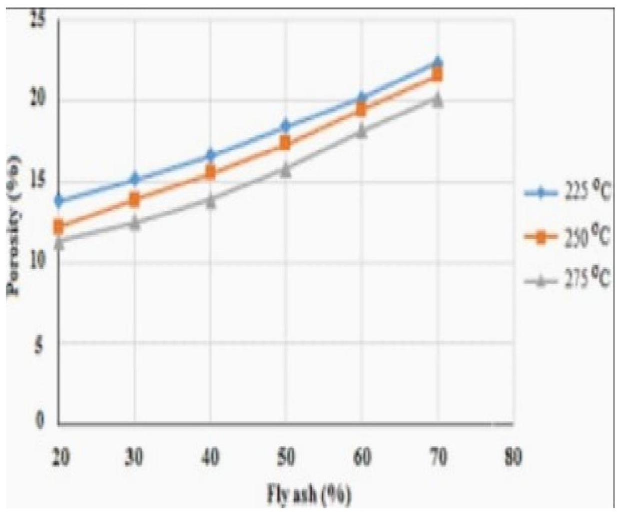

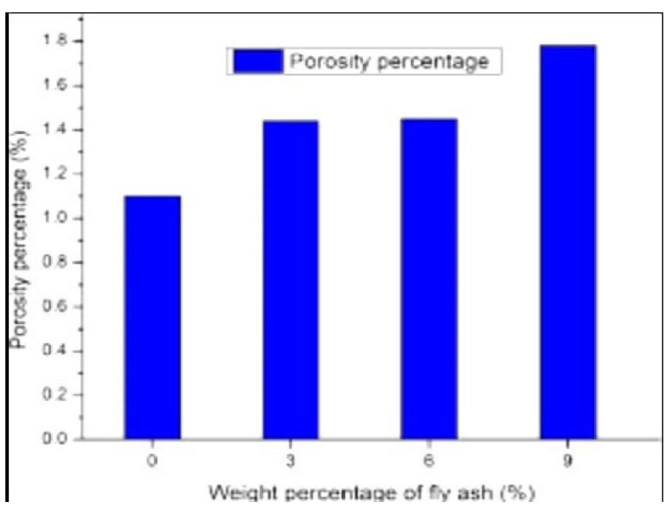

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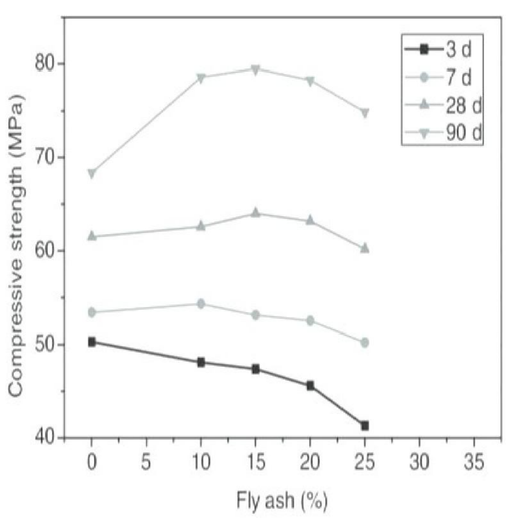
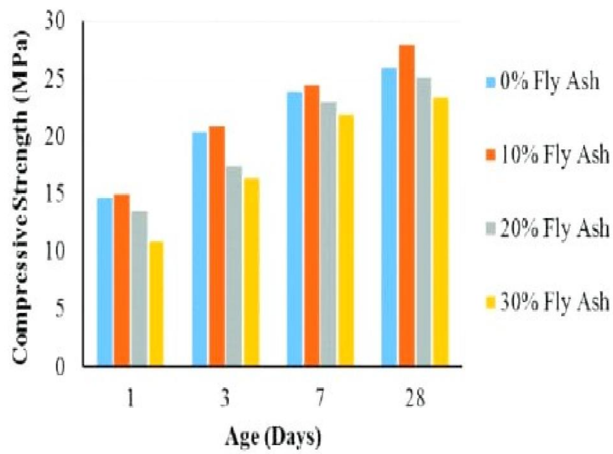
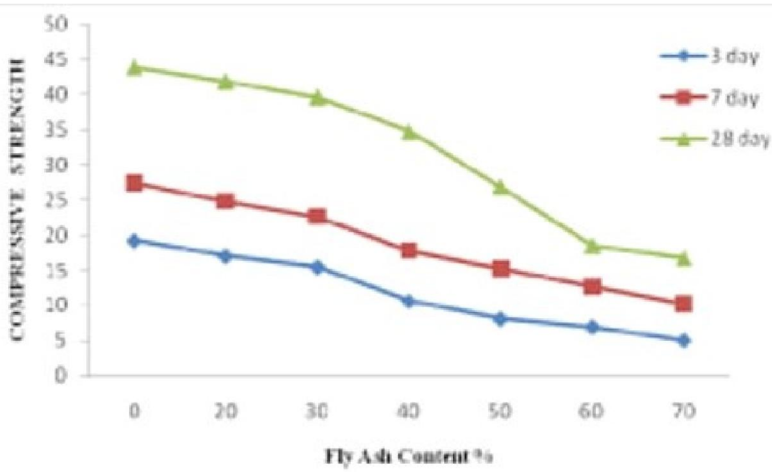
Porosity exhibited an inverse relationship with density. Increasing fly ash content resulted in a significant reduction in porosity up to 40 wt%, owing to efficient pore filling and enhanced matrix–filler interaction. The combined action of starch and cellulose derivatives contributed to improved matrix continuity, while lignin-based resin enhanced rigidity.
A marginal increase in porosity at higher fly ash content is attributed to agglomeration effects, which can create localized voids [17].

5.3 Compressive Strength







Compressive strength increased markedly with increasing fly ash content up to 40 wt%. Fly ash particles act as rigid fillers that enhance load-bearing capacity and facilitate efficient stress transfer across the matrix. Reduced porosity and improved interfacial bonding further contributed to strength enhancement.
Beyond the optimum filler content, a slight decline in strength was observed due to excess filler leading to agglomeration and reduced binder continuity. Similar trends have been reported in fly ash-based composite systems [17,18].

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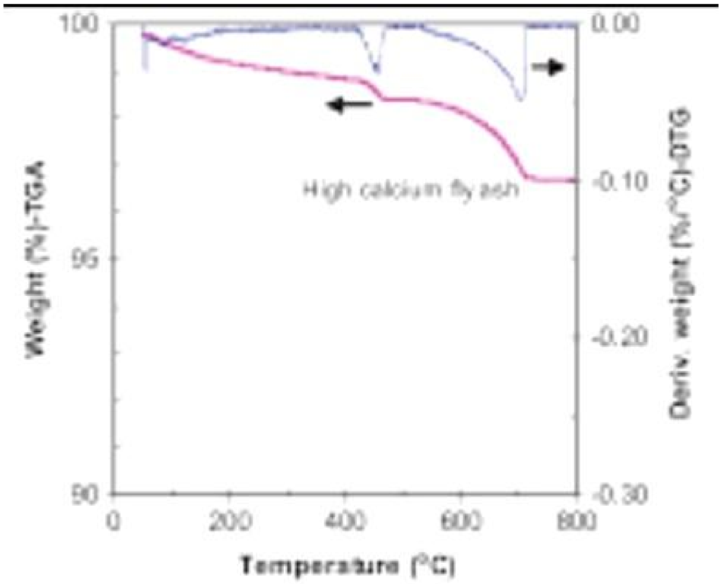
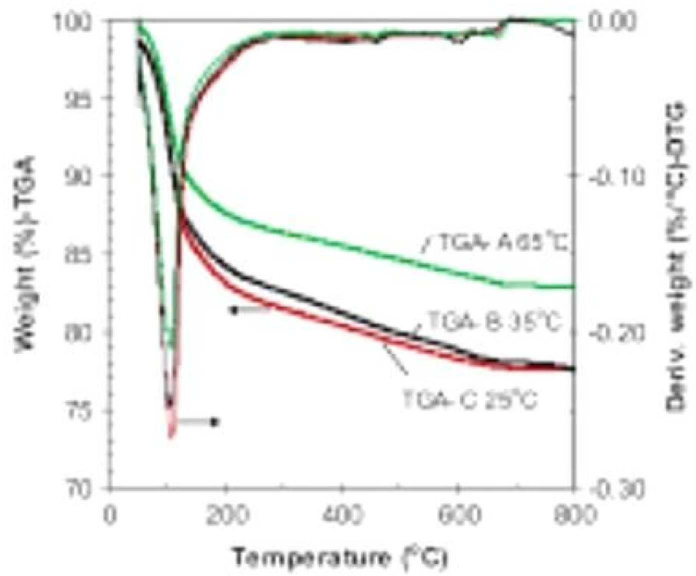
5.4 Thermogravimetric Analysis (TGA)



(a)



(b)

Thermogravimetric analysis demonstrated improved thermal stability of fly ash-based composites compared to the binder-only system. The onset of thermal degradation shifted to higher temperatures with fly ash incorporation, and higher residual mass was observed at elevated temperatures.

The enhanced thermal resistance is attributed to the inorganic nature of fly ash, which acts as a thermal barrier, and the char-forming tendency of lignin-based resin [19–21].

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5.5 Environmental Safety and Sustainability

Leachability assessment revealed negligible release of heavy metals, confirming effective immobilization of fly ash within the bio-organic matrix [22,23]. The use of renewable binders and industrial waste significantly reduces environmental impact and supports circular economy principles.

VI. APPLICATIONS

The developed bio-organic composites are suitable for use in sustainable construction materials, thermal insulation panels, agricultural soil conditioners, and environmental remediation applications.

VII. CONCLUSION

The present study establishes a green chemistry-based approach for the sustainable valorization of fly ash collected from CSTPS Chandrapur into bio-organic composite materials. The optimized incorporation of fly ash resulted in improved density, reduced porosity, enhanced compressive strength, and superior thermal stability. The use of biodegradable binders ensures environmental safety and sustainability. This research provides a viable and eco-friendly solution for fly ash management and sustainable material development.

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