Ash Management in Indian Power Plants: Current Status, Challenges and Future Directions

Subhajit Mukherjee[1]*, Suparna Paul[2] and Koyel Misra[1]

[1]Department of Basic Science, NSHM Knowledge Campus Durgapur, West Bengal-713212, India

[2]Department of Chemistry, NTPC Vindhyachal, Singrauli, Madhya Pradesh-486885, India.

***Corresponding Author**

DOI: https://doi.org/10.51244/IJRSI.2025.12110115

Received: 03 December 2025; Accepted: 09 December 2025; Published: 17 December 2025

ABSTRACT

Coal-fired thermal power plants in India generate large quantities of fly ash and bottom ash, creating significant environmental and operational challenges while also offering opportunities for resource recovery. This present manuscript presents a comprehensive overview of ash composition, mineral phases, and physicochemical characteristics, drawing on advanced analytical techniques such as XRD, XRF, SEM, particle-size analysis, and elemental mapping to illustrate the variability and complexity of fly ash generated across different combustion systems. The discussion highlights both the environmental risks associated with improper ash disposal—such as groundwater contamination, particulate pollution, and heavy-metal leaching—and the growing potential for transforming fly ash into value-added materials. Applications including zeolite synthesis, water-treatment adsorbents, supplementary cementitious materials, ceramics, alum production, and agricultural amendments are examined with support from recent literature. By synthesizing developments in characterization, utilization, and environmental assessment, the present manuscript emphasizes the need for integrated ash management strategies that align scientific understanding with sustainable industrial practices.

Keywords: Fly ash; Bottom ash; Ash management; Dry ash handling; Beneficiation; Fly ash utilization;

INTRODUCTION

Coal-based thermal power plants remain central to India's energy landscape, and their operation generates enormous quantities of fly ash and bottom ash as inevitable by-products of combustion [1]. Managing this ash stream has become one of the country's most pressing environmental and operational challenges, not only because of the sheer volume produced but also due to its complex and highly variable physicochemical characteristics [2]. Fly ash, in particular, exhibits a wide spectrum of particle sizes, mineral phases, and chemical compositions influenced by coal type, combustion technology, and plant-specific operating conditions. These variations significantly affect its behavior, environmental impact, and suitability for downstream utilization, making detailed characterization through XRD, XRF, SEM, PSD analysis and other analytical methods essential [3].

In recent years, the perception of fly ash has shifted from that of a disposal burden to a valuable industrial resource, driven by advancements in materials science, environmental engineering, and circular economy initiatives. Research has demonstrated its potential in producing zeolites, adsorbents, geopolymers, cements, ceramics, alum, and agricultural amendments—applications that reduce environmental risks while offering economic benefits [4]. At the same time, concerns persist regarding heavy-metal leaching, water contamination, airborne particulate emissions, and long-term stability of ash dumps, highlighting the need for robust testing and responsible end-use pathways. India's policy landscape, with increasingly stringent utilization mandates and incentives for ash-based products, has accelerated adoption but also exposed gaps in logistics, quality consistency, and market absorption [5].

Against this backdrop, comprehensive ash management requires an integrated approach that combines scientific understanding of ash properties, technological innovation for beneficiation, and strategic deployment of diverse utilization avenues [6]. The subsequent sections of this chapter explore the composition of fly ash, characterization techniques, and the expanding portfolio of applications that together shape India's evolving strategy for sustainable ash management [A7].

COMPOSITION AND CLASSIFICATION OF FLY ASH

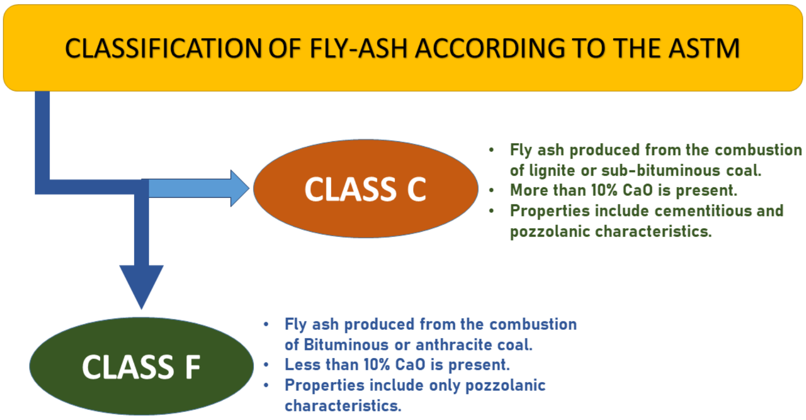
The mineral composition of fly ash (FA) is largely defined by its crystalline and glassy mineral fractions within the inorganic amorphous phase, along with varying amounts of partially combusted or unburned carbon [8,9]. Based on the time and conditions of formation, FA can be grouped into primary, secondary, and tertiary phases. Primary phases remain unchanged, whereas secondary phases—such as oxides and silicates—form during coal combustion. Tertiary phases, including minerals like portlandite and gypsum, develop as FA is transported. The major constituents of FA include numerous trace elements, with silicon, oxygen, calcium, aluminum, carbon, iron, magnesium, potassium, hydrogen, titanium, sodium, phosphorus, nitrogen, and barium being the most prominent [10,11].

The rate at which FA particles cool strongly influences the development of inorganic material: rapid cooling tends to generate fine glassy particles, while slower cooling promotes the growth of larger crystalline structures. Together, the amorphous and crystalline fractions make up the main inorganic composition of FA.

Fly ash is also categorized by its oxide composition, primarily consisting of CaO, SiO_2, Al_2O_3, and Fe_2O_3. An increase in CaO content typically corresponds to a decrease in SiO_2, Al_2O_3, and Fe_2O_3, whereas higher CaO is generally associated with elevated levels of alkalis (Na_2O and K_2O) and SO_3. [12]

Table 1: Major chemical compositions and their content in fly ash **[9].**

Component present	**Chemical formula**	**Content (%)**
Silicon Dioxide	SiO_2	59.4
Aluminium Oxide	Al_2O_3	34.08
Iron Oxide	Fe_2O_3	2.0
Lime	CaO	0.22
Sulphur Trioxide	SO_3	0.05
Magnesium Oxide	MgO	0.43



- Fly ash produced from the combustion of lignite or sub-bituminous coal.
- More than 10% CaO is present.
- Properties include cementitious and pozzolanic characteristics.

- Fly ash produced from the combustion of Bituminous or anthracite coal.
- Less than 10% CaO is present.
- Properties include only pozzolanic characteristics.

Figure 1: Classification of fly ash according to ASTM.

The density of FA is influenced by its iron and carbon content: greater carbon concentrations lower the density, while higher iron content raises it. Carbon levels also impact the water demand and workability of FA. Differences in carbon content between FA types are evaluated using the loss on ignition (LOI), which increases when more unburned carbon is present. As a result, Class F fly ash typically exhibits a higher LOI than Class C. **Figure 1** provides an overview of the key distinctions between Class C and Class F fly ash as defined by ASTM [13].

Fly ash is composed primarily of silicon dioxide (SiO2), aluminum oxide (Al2O3), iron oxide (Fe2O3), and calcium oxide (CaO) [10,11]. It also contains trace amounts of other elements like mercury, arsenic, and lead, as well as unburnt carbon. The specific composition varies depending on the type of coal burned, which is why fly ash is often classified as either Class F (low calcium) or Class C (high calcium) [8].

Major components:

Silicon dioxide (SiO_2): A primary component, often found in a glassy, amorphous structure.

Aluminum oxide (Al_2O_3): Another major constituent of fly ash.

Iron oxide (Fe_2O_3): A significant component, although the amount can vary.

Calcium oxide (CaO): Present in varying amounts, with Class C fly ash typically having higher levels than Class F.

Minor and trace components:

Magnesium, potassium, sodium, titanium, and sulfur are also present in lesser degrees [10].

Heavy metals: Trace amounts of toxic heavy metals can be found, including arsenic, beryllium, cadmium, chromium, lead, mercury, and vanadium.

Unburnt carbon: May be present, especially in certain types of fly ash.

Indian coal, often of higher ash content than many global coals, produces fly ash with variable chemistry depending on coal rank, beneficiation and combustion conditions; this heterogeneity affects downstream utilization.

Cenosphere spheres, anhydrous phases, and unburnt carbon (loss on ignition) influence ash reactivity and suitability for specific applications. Standard characterization (particle size distribution, chemical assays, mineralogy) is essential for matching ash to uses.

FLY ASH TESTING AND CHARACTERIZATION TECHNIQUES

3.1. X- ray diffraction (XRD)

X-ray diffraction (XRD) is used to qualitatively determine the crystalline phases present in fly ash. In this technique, electrons strike the solid sample, causing it to emit X-rays. When these X-rays interact with the crystal lattice, their behavior varies: some are diffracted according to the degree of crystallinity, while others penetrate deeper into the material until they encounter a crystal plane.

During analysis, the XRD instrument records the angles and intensities of both scattered and diffracted X-rays. These measurements are then plotted to generate a diffractogram, which displays the relationship between diffraction angle and the corresponding diffracted intensity.

Nath et al. displayed the X-ray diffraction patterns, where the dominant peaks in the CFA profile correspond to the crystalline phases of quartz and mullite [14]. The broad humps observed around $2\theta = 15°$ and $35°$ represent the presence of amorphous phases. Variations in the CFA diffraction patterns (Fig. 2) can arise from differences in the types of coal used (such as bituminous or lignite) as well as the combustion methods employed—whether pulverized coal combustion, fluidized bed combustion, or the burning of coal alone or in combination with petroleum coke or biomass [15].

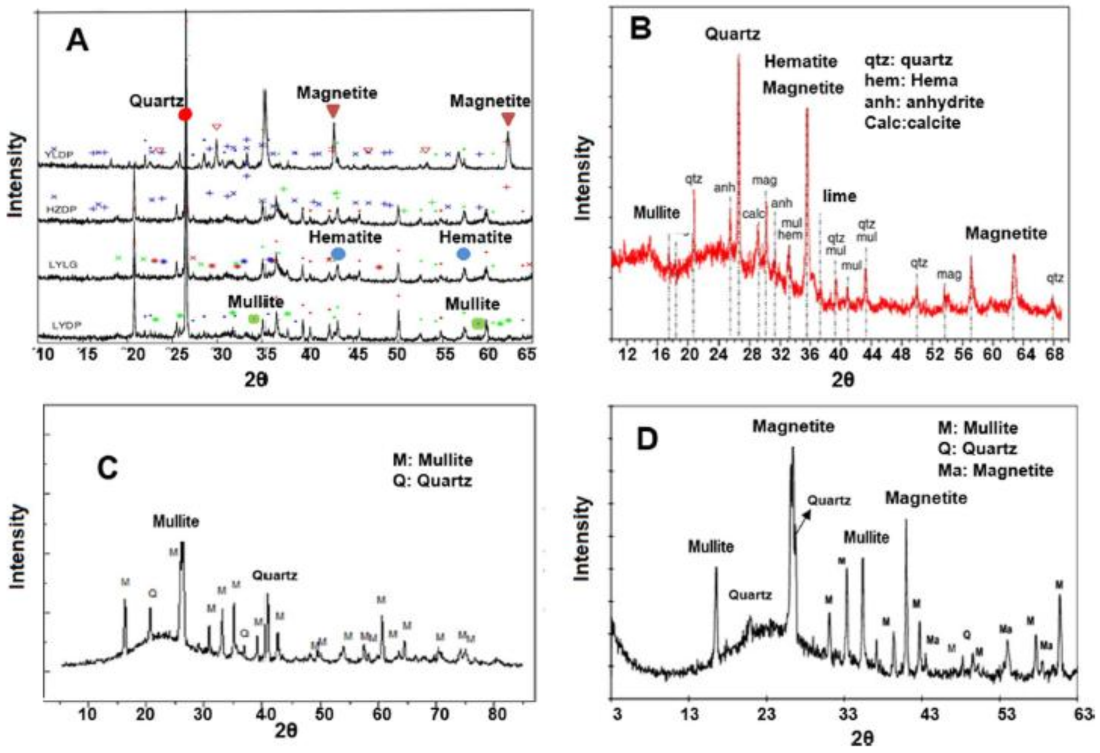


Figure 2: Comparison of the XRD images of four CFAs from different reports a Australian brown coal fly (Tennakoon et al. 2015); b Thermal coal power plant Germany (Li et al. 2016); c Circulating fludized bed fly ash Xishan Thermal Power Plant China (Liu et al. 2019); d Silico aluminous fly ash from power station, Albi, France (Benezet et al. 2008)

3.2. X-ray fluorescence (XRF)

X-ray fluorescence (XRF) is commonly used to determine the overall oxide composition of various fly ash samples. It is also often applied to estimate the amount of amorphous material, which is calculated by subtracting the crystalline phase from the total measured oxide content. In this method, fly ash is exposed to high-energy X-rays that stimulate the emission of fluorescent, or secondary, X-rays. These secondary emissions enable both qualitative and quantitative identification of the oxide constituents in fly ash [16].

3.3. Particle size distribution

Laser diffraction is a widely used technique for determining the particle size distribution of fly ash (FA). In this method, a laser beam is directed at the sample to generate a distribution profile for FA or other particulate materials. When the particles interact with the light beam, electrons are displaced, causing the light to scatter. This scattering occurs due to diffraction, refraction, and reflection, although some light may also be absorbed [17].

The instrument analyzes the resulting diffraction pattern and interprets the interaction between the particles and the light using a mathematically derived model, typically based on either Fraunhofer or Mie theory. A Fourier transform lens focuses the diffracted light, converting the incident energy into electrical signals. The particle size is then determined from the angle formed between the incoming and scattered light [18].

3.4. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is employed to examine the amorphous phase composition of fly ash (FA). In SEM analysis, a focused electron beam penetrates the sample to a depth of roughly 1 µm. As the beam is directed at a specific point, detectors capture the resulting signals and convert them into intensity values, which are then used to construct an image on a connected computer. When secondary electrons are detected, the resulting image reveals the surface topography. These electrons are released when the incoming beam dislodges valence electrons from atoms in the sample, and the number of electrons attracted to the detector determines the strength of the signal [19]. Different SEM studies have been performed to understand the shape of the particles. Fly ash exhibits a wide range of morphological forms, and no two samples appear exactly alike. Figures 3a, 3b, and 3c illustrate three common CFA particle shapes: spherical, oval, and irregular [20-23].

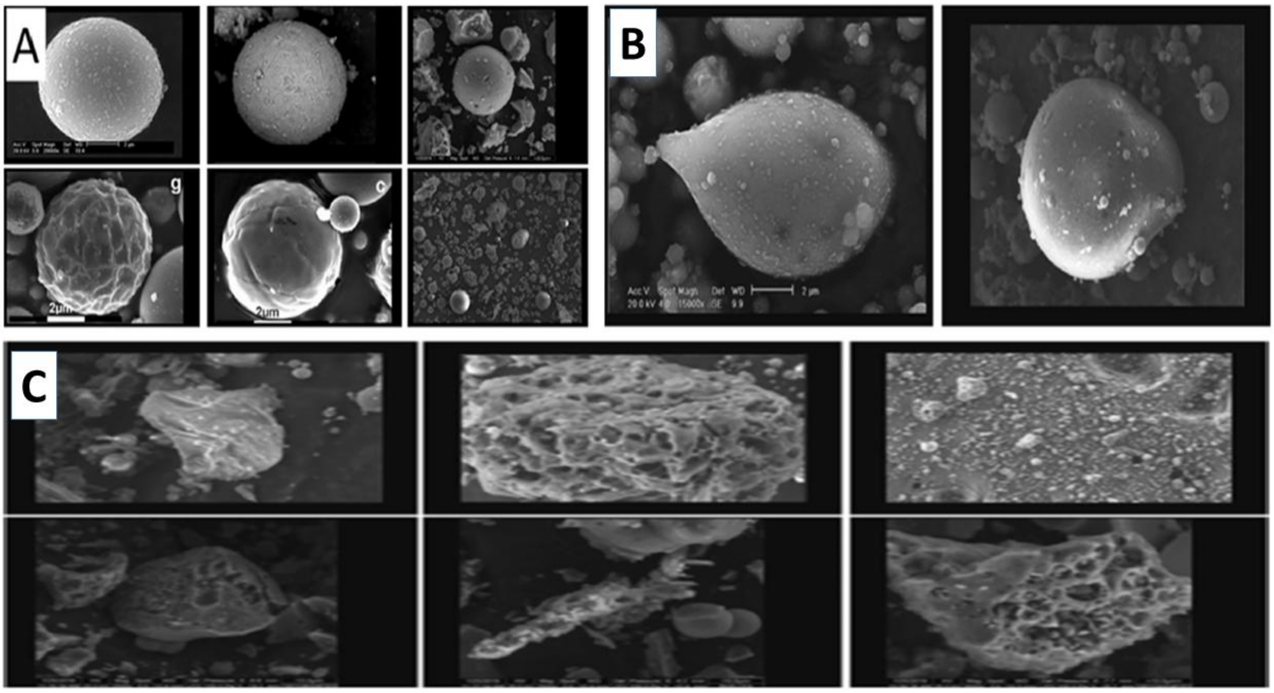


Figure 3: (a) CFA with spherical shape [21-23]; (b) CFA with oval shape [21, 23]; (c) CFA particle with Irregular shape [23].

To analyze the elemental composition of the amorphous particles, energy-dispersive X-ray analysis (EDXA) is carried out. When the electron beam strikes the specimen surface, it generates X-rays characteristic of the elements present. The EDXA system interprets these emissions to identify the chemical makeup of the amorphous particles, which are typically spherical and measure between 1 and 5 µm in diameter. A built-in measuring tool is used to determine particle size, and only those within the 1–5 µm range are selected for EDAX point analysis. In contrast, examining particles between 150 and 200 µm provides a broader evaluation of the entire fly ash sample.

Quantitative analysis focuses on eight key elements—iron, oxygen, calcium, aluminum, potassium, sodium, carbon, and silicon. These elements are subsequently converted to their oxide forms, and each measurement point is plotted on a ternary diagram for further interpretation [24].

FRAMEWORK LINKING FLY ASH PROPERTIES TO UTILIZATION PATHWAYS

Fly ash utilization **(Table 2)** is strongly governed by its intrinsic properties, particularly mineralogy, loss on Ignition (LOI), particle size distribution, and amorphous content. High silica–alumina mineralogy with phases like quartz and mullite favors applications in cement, geopolymers, ceramics, and zeolite synthesis, while iron- and calcium-rich phases enable use in catalysts, adsorbents, and soil stabilization. LOI determines suitability for concrete—low-LOI ash is preferred for cementitious applications, whereas high-carbon ash is better suited for adsorbents or geotechnical fill. Particle size distribution controls reactivity and placement behavior: fine particles support high-performance cement, geopolymer, and adsorption applications, while coarser fractions are used in road bases and embankments. The proportion of amorphous aluminosilicate phases further dictates reactivity, with high amorphous content enabling pozzolanic reactions critical for cement, geopolymer, and zeolite production, and lower amorphous content shifting use toward filler and structural applications.

Table 2: Fly ash properties related to utilization pathways

Fly Ash Property	Influence	Best Utilization Pathways
Mineralogy	Reactivity, phase-specific functionality	Cement, geopolymers, ceramics, catalysts, adsorbents
LOI	Carbon content affects performance	Low LOI → concrete; high LOI → adsorbents, mine fill
Particle size distribution	Surface area & packing behavior	Fine → reactive products; Coarse → geotechnical uses
Amorphous Content	Governs pozzolanic reaction	Geopolymer, zeolite, cement blending

APPLICATIONS OF FLY ASH

5.1. Synthesis of zeolites

Fly ash has emerged as an economical and efficient precursor for zeolite synthesis due to its high content of reactive aluminosilicate minerals. The amorphous silica and alumina in fly ash readily dissolve under alkaline hydrothermal conditions, enabling the formation of various zeolitic structures such as zeolite A, X, P, Y, and sodalite. One of the synthetic scheme has been shown in **Figure 4** as described by Sabriye Piskin et al. in the year 2019 [25]. Using fly ash not only reduces the cost of producing zeolites but also supports waste valorization and environmental sustainability by diverting large quantities of industrial ash from landfills. Zeolites synthesized from fly ash have been successfully applied in ion exchange, wastewater treatment, gas adsorption, catalytic cracking, and heavy metal removal, demonstrating performance comparable to or even exceeding that of conventional zeolites. Numerous studies have highlighted these advantages—Hollman et al. reported the successful conversion of Class F fly ash into zeolite P under mild hydrothermal conditions [26], while Querol et al. [27] and Singer et al. [28] demonstrated the suitability of fly-ash-derived zeolites for environmental remediation and industrial separation processes. Thus, fly ash serves as a promising low-cost raw material for sustainable zeolite production with wide-ranging applications.

Figure 4: Synthetic scheme for the preparation of zeolite from flyash as described by Sabriye Piskin et al. in the year 2019 [25].

5.2. Water treatment

Fly ash is increasingly being converted into efficient adsorbents. For instance, a 2024 study prepared modified high-silica fly ash materials — a mesoporous silica–based material (MSM) and a sodium-dodecyl-sulfate–modified fly ash (SDS-FA) — via an ultrasound-assisted alkali-fusion and hydrothermal method. Under optimal conditions (adsorbent dosage 2 g L^{-1}, pH ~9, contact time 150 min, pollutant concentration 100 mg L^{-1}), these materials removed ~ 92.7% (MSM) and ~ 84.6% (SDS-FA) of methylene blue from solution, far outperforming raw fly ash. The adsorption followed Langmuir isotherm behavior and pseudo-second-order kinetics, indicating monolayer chemisorption as the dominant mechanism [29,30]. Similarly, chemically treated coal fly ash has been shown to remove hazardous organic dyes — one study reported a treated fly ash achieving up to 99.7% removal of Direct Blue 78 dye under favorable conditions, after its surface area was increased substantially from ~9.6 to ~60.4 m^2g^{-1} [31]. Moreover, for heavy-metal removal, simpler modifications can also yield considerable results: a 2022 study demonstrated that NaOH-treated fly ash effectively adsorbed Cu(II) ions from aqueous solution, validating pseudo-second-order kinetics and suggesting practical viability for wastewater treatment [32,33].

Beyond adsorption, there's growing interest in converting fly ash into more stable, structured materials. One promising route is the production of fly ash based geopolymers, where aluminosilicate-rich FA reacts with alkaline activators (e.g. NaOH + sodium silicate) to form porous, polymeric networks. Such geopolymers have been shown to immobilize heavy metals and dyes effectively — for example, a 2025 study reported that geopolymers derived from fly ash removed organic dyes from water, highlighting their potential as low-cost, high-performance adsorbents [34]. Another recent advancement combined photocatalysis and membrane filtration: a 2025 work synthesized a ceramic membrane from FA modified with TiO_2–ZnO, which under visible light achieved ~77% degradation of the antibiotic tetracycline within 100 minutes, while retaining ~73% efficiency after five reuse cycles — demonstrating both pollutant removal and membrane reusability [35]. Additionally, a 2024 study evaluated the durability and heavy-metal immobilization capacity of fly-ash-based geopolymers under leaching and aging conditions, confirming their structural stability and long-term potential for safe sequestration of toxic metals in polluted water environments [36]. A schematic representation is given in **Figure 5** as was shown by V. Saxena et al in 2025 [37].

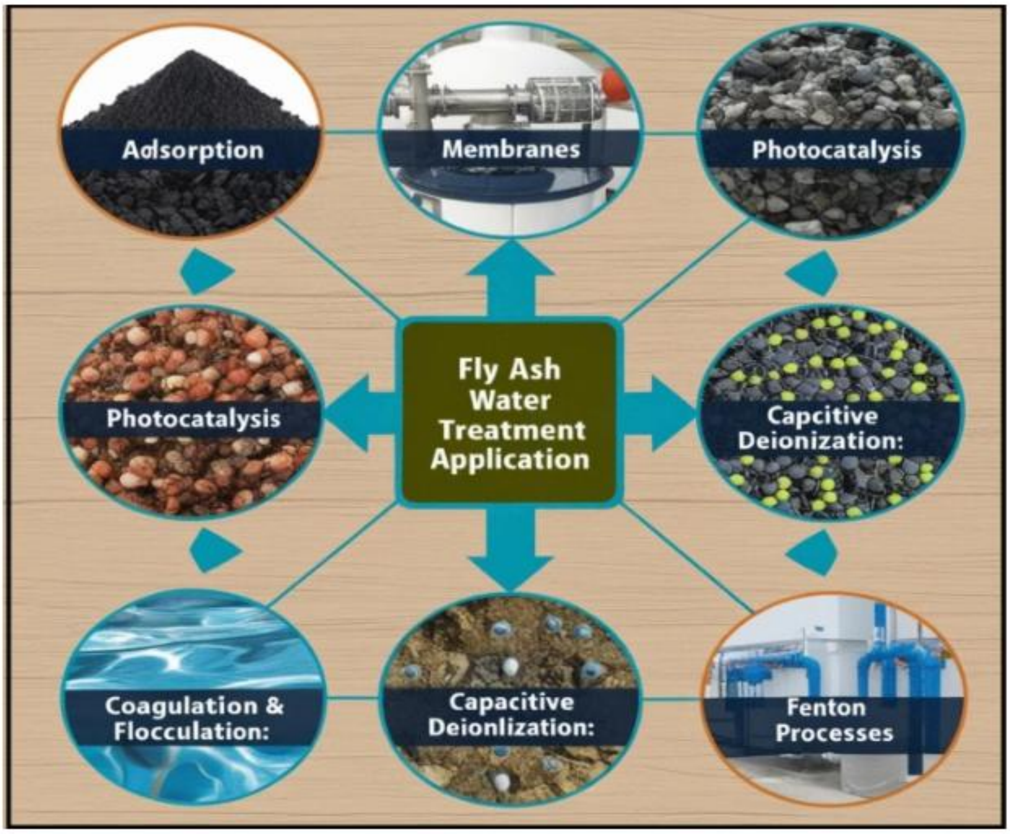


Figure 5: Application of fly ash in water treatment [37].

5.3. Supplementary cementitious material

Fly ash is widely used as a partial replacement for Portland cement and as the primary binder in geopolymer cements — approaches that substantially reduce embodied CO_2 and improve many concrete properties. When used as a **supplementary cementitious material (SCM)** at typical replacement levels (10–30%), FA improves workability, lowers heat of hydration, and enhances long-term strength and durability (better resistance to sulfate attack, chloride ingress and alkali-silica reaction) compared with plain OPC concrete [38]. At higher replacement levels or in alkali-activated formulations, low-calcium (Class F) fly ash can be transformed into **geopolymer binders** (activated by $NaOH/Na_2SiO_3$), producing eco-efficient concretes with competitive mechanical performance and excellent chemical resistance; recent reviews and field-oriented studies highlight geopolymer concrete's readiness for structural use while noting scale-up, curing, and raw-material variability as remaining implementation challenges [39].

5.4. Ceramic industry

Fly ash is rich in metal oxides such as Al_2O_3, SiO_2, Fe_2O_3 and CaO, making it an inexpensive and attractive raw material for ceramic production. Its inherently fine, powder-like texture enables it to blend directly into ceramic mixtures with minimal or no pretreatment [40]. Numerous studies have explored the fabrication of sintered products and glass-ceramic materials derived from fly ash, utilizing processes such as exhaust-gas heat activation, refractory metal coating formation, and electronic packaging applications. More recently, fly ash has been adopted as a substitute for kaolinite in the synthesis of cordierite ceramics [41; 42].

The transformation of raw fly ash into glass or ceramic products primarily depends on temperature conditions and the presence of additional reagents, which govern the structure of the final material. Glass-ceramic compositions containing Al_2O_3–Li_2O–SiO_2 are industrially valuable because of their very low or even negative thermal expansion behavior; however, conventional production remains costly due to the reliance on high-purity reactants [42]. To reduce production costs, coal bottom ash has been explored as a feedstock for synthesizing $Li_2Al_2Si_3O_{10}$, yielding a material with an 18% lower thermal expansion coefficient compared to its commercially manufactured counterpart [43]. In another study, $Li_2Al_2Si_3O_{10}$ prepared directly from fly ash exhibited fine crystallites and a well-developed microstructure [44].

Cordierite, which exists in three polymorphs including the high-temperature phase known as indialite, has an orthorhombic crystal structure and is highly valued for its low thermal expansion, excellent refractoriness, and low dielectric constant. Owing to these properties, cordierite ceramics are widely used in applications such as gas-turbine engine components, heat exchangers, and catalyst supports for emission control systems.

5.5. Synthesis of Alum

Fly ash has gained attention as a promising raw material for the preparation of alum due to its high content of reactive aluminosilicate phases [45]. In alum production, fly ash serves as a low-cost source of aluminum, which can be extracted through acid leaching—typically using sulfuric acid—to produce aluminum sulfate (alum). During this process, the acidic medium dissolves the alumina present in fly ash, forming a solution that can be purified and crystallized into alum [46]. This approach not only reduces the dependence on conventional bauxite-based alum manufacturing but also provides an environmentally beneficial route for utilizing industrial waste [47]. Additionally, the conversion of fly ash into alum mitigates ash disposal challenges and supports circular economy practices by transforming a by-product of coal combustion into a valuable chemical used in water treatment, paper sizing, and dyeing industries [48].

5.6. Agricultural fertilizer production

Fly ash has emerged as a useful supplementary material in agricultural fertilizer production due to its rich composition of essential plant nutrients such as silica, calcium, magnesium, potassium, and trace elements [49]. When incorporated into fertilizer formulations, fly ash enhances soil structure, improves aeration, and increases the water-holding capacity of degraded soils. Its alkaline nature also helps neutralize acidic soils, promoting better nutrient availability for crops. Additionally, fly ash can act as a carrier in the production of biofertilizers and slow-release fertilizers, aiding in the gradual supply of nutrients while reducing nutrient leaching [50,51]. By partially substituting conventional mineral inputs, the use of fly ash not only lowers production costs but also supports sustainable waste management by converting an industrial by-product into a valuable agricultural resource. These applications of fly ash are presented in **Figure 6** [52].

Figure 6: Applications of fly ash [52].

6. Conclusion

Effective ash management has become a pivotal component of India's transition toward more sustainable thermal power operations. The present manuscript demonstrates that fly ash and bottom ash, once regarded primarily as waste materials, possess significant potential for value addition when supported by detailed characterization and scientifically guided utilization strategies. Advanced analytical tools such as XRD, XRF, SEM, particle-size analysis, and elemental mapping reveal the wide heterogeneity of ash generated across different combustion systems, underlining the need for plant-specific assessments before end-use applications.

The diverse avenues of fly ash utilization—including zeolite synthesis, water-treatment adsorbents, geopolymer and cementitious materials, ceramics, alum production, and agricultural soil amendments—showcase its versatility as a functional industrial resource. These pathways not only mitigate the environmental risks associated with ash disposal, such as heavy-metal leaching, groundwater contamination, and fugitive dust emissions, but also contribute to circular-economy objectives by converting an abundant by-product into valuable materials. However, challenges persist regarding quality variability, logistics, long-term environmental stability, and the need for optimized beneficiation processes to ensure consistency and safety in downstream applications.

Overall, this manuscript highlights that sustainable ash management requires an integrated framework that combines scientific characterization, technological innovation, regulatory support, and industry-level coordination. By strengthening utilization channels and promoting resource-efficient practices, India can significantly reduce the ecological footprint of coal-based power generation while fostering new technological and economic opportunities. The future of ash management lies in advancing high-value applications, improving beneficiation techniques, and embedding circular-economy principles into energy and materials policy at a national scale.

REFERENCES

1. S. Kar and P. Paul, Cleaner Mater., 2023, 9, 100202.
2. A. Roy, S. Mukherjee and B. Das, Environ. Pollut., 2023, 319, 120993.
3. J. Ma, X. Qi, W. Song, H. Li and R. Zhang, J. Hazard. Mater., 2024, 455, 131215.
4. V. Kumar and R. Singh, Atmos. Environ., 2024, 286, 119265.
5. S. Mohapatra and R. Patel, Resour. Conserv. Recycl. Adv., 2023, 19, 200217.
6. X. Li, Y. Zhang, Z. Wang and N. Liu, Powder Technol., 2024, 420, 118376.
7. P. Sharma and M. Chandel, J. Clean. Prod., 2023, 385, 135746.

8. Dai, S. et al., 2012. Petrology, mineralogy, and geochemistry of the Ge-rich coal from the Wulantuga Ge ore deposit, 90, 72–99.
9. Khairul Nizar Ismail, Kamarudin Hussin and Mohd Sobri Idris, J. Nucl. Relat. Technol., 2007, 4, 47–51.
10. S. V. Vassilev and C. G. Vassileva, Fuel, 2007, 86, 1490–1512.
11. IOP Conf. Ser.: Mater. Sci. Eng., 2017, 263, 032010.
12. A. Bhatt et al., Case Stud. Constr. Mater., 2019, 11, e00263.
13. J. C. Hower, A. S. Trimble and C. F. Eble, Fuel Process. Technol., 2001, 73, 37–58.
14. S. K. Nath, S. Maitra, S. Mukherjee and S. Kumar, Constr. Build. Mater., 2016, 111, 758–765.
15. Z. Wang et al., Microporous Mesoporous Mater., 2016, 222, 226–234.
16. K. Kruse et al., CTR Tech. Rep., 2012, 6648(1).
17. J. M. Veranth et al., Fuel, 2000, 79, 1067–1075.
18. M. Cyr et al., Cem. Concr. Res., 2001, 34, 342–350.
19. R. T. Chancey, PhD Thesis, 2008.
20. N. Wang et al., J. Hazard. Mater., 2020, 396, 122725.
21. P. Brown, T. Jones and K. BéruBé, Environ. Pollut., 2011, 159, 3324–3333.
22. B. Rubio et al., J. Environ. Manag., 2008, 88, 1562–1570.
23. M. Sow et al., Fuel, 2015, 162, 224–233.
24. A. Sambangi and E. J. M. T. P. Arunakanthi, Mater. Today Proc., 2021, 45, 6687–6693.
25. O. Dere Ozdemir and S. Piskin, Waste Biomass Valor., 2019, 10, 143–154.
26. G. G. Hollman, G. Steenbruggen and M. Janssen-Jurkovičová, Fuel, 1999, 78, 1225–1230.
27. X. Querol et al., Int. J. Coal Geol., 2002, 50, 413–423.
28. A. Singer and V. Berkgaut, Appl. Clay Sci., 1995, 10, 471–478.
29. X. Guo et al., RSC Adv., 2024, 14, 21342–21354.
30. X. Guo et al., RSC Adv., 2025, 15, 35158–35174.
31. A. Eteba, M. Bassyouni and M. Saleh, Int. J. Environ. Sci. Technol., 2023, 20, 7589–7602.
32. G. Buema et al., Water, 2021, 13, 207.
33. W. Jadaa, Clean Technol., 2024, 6, 221–279.
34. D. V. Trajković et al., Separations, 2025, 12, 299.
35. L. Sawunyama et al., Discover Nano, 2025, 20, 1.
36. X. Ren et al., RSC Adv., 2024, 14, 12580–12592.
37. V. Saxena et al., Water Air Soil Pollut., 2025, 236, 731.
38. D. K. Nayak et al., Cleaner Mater., 2022, 6, 100143.
39. B. K. Shukla et al., Mater. Today, Proc., 2023, 93, 257–264.
40. M. Erol et al., Fuel, 2008, 87, 1334–1340.
41. Y. He et al., Ceram. Int., 2005, 120, 265–269.
42. Z. Yao et al., J. Hazard. Mater., 2015, 141, 105–121.
43. C. Kniess et al., J. Non-Cryst. Solids, 2007, 353, 4819–4822.
44. Z. Yao et al., J. Eur. Ceram. Soc., 2012, 21, 877–881.
45. S. Mandal and S. Mohanta, Int. J. Sci. Res. Arch., 2024, 5, 495–502.
46. J. Zhang, L. Wang and M. Chen, Adv. Mater. Res., 2013, 734–737, 1551–1556.
47. X. Li et al., RSC Adv., 2022, 12, 37626–37638.
48. H. C. Park, Y. J. Park and R. Stevens, Mater. Sci. Eng. A, 2004, 367, 201–207.
49. K. M. Spark and R. S. Swift, Aust. J. Soil Res., 2008, 46, 578–584.
50. R. M. Hamidi et al., RSC Adv., 2022, 12, 33187–33199.
51. S. Pradhan et al., Int. J. Plant Soil Sci., 2025, 37, 900–910.
52. Daswell, fly ash properties and uses (https://daswell.com/blogs/fly-ash-properties-source-advantages-uses/).