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A Review on Fly Ash-Derived Smart and Functional Materials: Recent Advances, Challenges, and Future Prospects

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ABSTRACT

Fly ash is one of the most abundant industrial by-products generated from coal combustion in thermal power plants. The large-scale accumulation of fly ash poses serious environmental challenges, including land contamination and air pollution. However, due to its unique chemical composition and physicochemical properties, fly ash has gained significant attention as a potential raw material for the development of advanced functional and smart materials. This review paper presents a comprehensive overview of the utilization of fly ash in smart materials and advanced composites. The chemical composition, classification, and physicochemical properties of fly ash are discussed to highlight its suitability as a functional filler and reinforcement material. Various synthesis techniques for fly ash-based smart materials, including geo-polymerization, polymer composite fabrication, and nanocomposite synthesis, are reviewed. Applications of fly ash-derived smart materials in areas such as construction materials, electromagnetic shielding, sensors, energy storage, and environmental remediation are critically analysed. Additionally, characterization techniques including X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and thermal analysis are discussed for evaluating the structural and functional properties of these materials. Finally, the challenges, environmental benefits, and future research directions for the development of fly ash-based smart materials are highlighted. The review demonstrates that fly ash has immense potential as a sustainable resource for advanced materials development and contributes to circular economy and waste valorization.

1. Introduction

The rapid growth of industrialization and energy demand has resulted in the generation of enormous quantities of industrial by-products worldwide. Among these wastes, fly ash is one of the most significant residues generated from coal-fired thermal power plants. Globally, hundreds of millions of tons of fly ash are produced annually, posing serious environmental and disposal challenges. Fly ash is mainly composed of silica, alumina, iron oxides, calcium oxide, and other trace elements [1]. Due to its pozzolanic properties and fine particle size, fly ash has traditionally been used as a supplementary cementitious material in construction. However, recent research has focused on converting this industrial waste into value-added materials such as smart materials, nanocomposites, and functional ceramics [2].

Smart materials are materials that can respond to external stimuli such as temperature, pressure, electric field, magnetic field, moisture, or chemical environment by changing their properties. These materials are widely used in sensors, actuators, biomedical devices, aerospace systems, and energy technologies. Fly ash provides a promising raw material for the development of such advanced materials because of its chemical composition, structural characteristics, and economic advantages [3].

Rapid industrialization and energy consumption have led to the generation of enormous quantities of industrial waste worldwide (Fig. 1). Among these wastes, fly ash is one of the most significant by-products produced during coal combustion in thermal power plants. The annual global production of fly ash is estimated to exceed hundreds of millions of tons, with countries such as India, China, and the United States being major contributors. Improper disposal of fly ash can lead to severe environmental issues such as soil contamination, groundwater pollution, and airborne particulate hazards [4]. Fly ash primarily consists of silica, alumina, iron oxide, calcium oxide, and other trace minerals, making it a valuable secondary resource for various industrial applications. Due to its pozzolanic properties and spherical particle morphology, fly ash has been widely used as a supplementary cementitious material in construction.

In recent years, researchers have explored the potential of fly ash as a precursor material for advanced functional materials and smart materials. Smart materials are defined as materials that can respond to external stimuli such as temperature, pressure, electric fields, magnetic fields, or chemical environments by altering their properties. These materials are widely used in sensors, actuators, self-healing systems, and energy storage devices. The presence of reactive silica and alumina phases in fly ash enables the synthesis of various advanced materials including geopolymers, polymer composites, ceramic composites, and nanostructured materials. These materials exhibit enhanced mechanical strength, thermal stability, electrical conductivity, and environmental resistance [5].

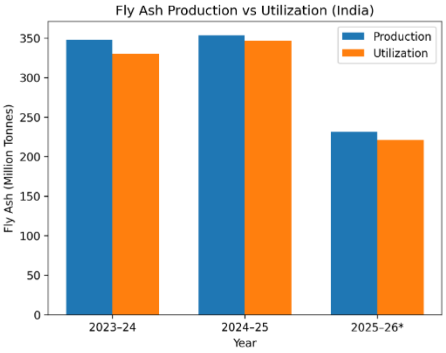

Fig. 1 Fly-ash generation and utilization during the period 2023-24 to 2025-26

This review focuses on the recent advances in fly ash utilization for the development of smart materials. It highlights the synthesis methods, properties, applications, and future perspectives of fly ash-based smart materials.

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2. Sources and Classification of Fly Ash

Fly ash is produced during the combustion of pulverized coal in thermal power plants. When coal is burned at high temperatures, the mineral impurities melt and form tiny spherical particles that are carried along with flue gases. These particles are captured using electrostatic precipitators and collected as fly ash. According to ASTM standards, fly ash is classified into two major categories [6].

2.1 Class F Fly Ash

Produced from burning anthracite or bituminous coal. It contains low calcium content and exhibits strong pozzolanic properties.

2.2 Class C Fly Ash

Produced from lignite or sub-bituminous coal. It contains higher calcium content and possesses both pozzolanic and cementitious properties. The composition and reactivity of fly ash depend on coal source, combustion conditions, and collection systems used in power plants (Table 1).

Table 1 Comparison of major fly ash types

Property	Class F Fly Ash	Class C Fly Ash
Coal Source	Anthracite or Bituminous	Lignite or Sub-bituminous
Calcium Content	Low (<10% CaO)	High (>20% CaO)
Key Characteristic	Pozzolanic; requires activator (cement/ lime)	Both pozzolanic and self-cementing.
Primary Advantage	High resistance to sulfate attack; lower heat.	Faster early strength development

3. Physicochemical Properties of Fly Ash

Fly ash possesses unique physicochemical properties that make it suitable for advanced material synthesis. The general chemical composition is including silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and trace metals (Table 2).

Table 2 Chemical composition of fly ash

Chemical compound	Pozzolan type			Cement
	Class F	Class C	Class N	
SiO	54.90	39.90	58.20	22.60
Al_2O_3	25.80	16.70	18.40	4.30
Fe_2O_3	6.90	5.80	9.30	2.40
CaO	8.70	24.30	3.30	64.40
MgO	1.80	4.60	3.90	2.10
SO_3	0.60	3.30	1.10	2.30
Na_2O and K_2O	0.60	1.30	1.10	0.60

In term of its physical characteristics, fly ash particles are generally spherical with a particle size ranging from 1–100 μm. They exhibit low density, high surface area, and good thermal stability. These properties improve mechanical strength and durability when incorporated into composite materials (Table 3). The glassy amorphous phase present in fly ash enhances its reactivity in geopolymer and ceramic synthesis processes [7].

Table 3 Physical properties explain by different researchers

Property	Gümüşer [8]	N. Gamage, et al. [9]	Huang et al. [10]	Ghofur et al. [11]
Specific gravity	2.54	1.9-2.55	2.6	2.3
Moisture	13.60%		0.53%	19.75%
Fineness			13.80% in No.325	0.6-0.001mm
LOI			7.5	
Maximum dry density	1.65 g/cm^3	0.9-1.6 g/cm^3		1.53 g/cm^3
Uniformity coefficient	2.5	3.1-10.7		
Liquid limit	16.8			
Permeability	0.9 X 10^{-5} cm/s	10 - 5 x 10^{-3} cm/s		4.87 X 10^{-7} cm/s
Angel of internal friction		30°-40°		23°- 41°
Cohesion		Negligible		3.34 kPa
Compress index		0.05-0.4		0.15
Coefficient of consolidation				0.1-0.5 m^3/year

4. Application of Fly Ash in Smart Material

4.1 Fly Ash in Smart Material Development

Smart materials possess the capability to respond dynamically to external stimuli such as temperature, pressure, light, electric fields, or chemical environments. Fly ash has emerged as a promising precursor for the development of smart materials owing to its aluminosilicate-rich composition, porous structure, and excellent thermal stability. The presence of reactive silica (SiO_2) and alumina (Al_2O_3) facilitates the formation of advanced functional phases and composite matrices [12].

The key advantages of utilizing fly ash in smart material development include:

- Abundant and readily available industrial by-product
- Cost-effective raw material
- High silica and alumina content suitable for advanced material synthesis
- Excellent thermal stability and resistance to high temperatures
- Environmentally sustainable through waste valorization and reduced landfill disposal

These characteristics make fly ash a suitable candidate for the fabrication of responsive composites, structural ceramics, geopolymers, and functional coatings with potential applications in advanced engineering and environmental technologies.

4.2 Fly Ash-Based Geopolymer Materials

Geopolymers are inorganic polymeric materials synthesized through the reaction of aluminosilicate precursors with alkaline activating solutions. Fly ash is widely employed as a precursor in geopolymer production because of its high silica (SiO_2) and alumina (Al_2O_3) content, which facilitates the formation of a stable three-dimensional aluminosilicate network. Fly ash–based geopolymers exhibit several advantageous properties, including high compressive strength, excellent chemical resistance, low shrinkage, and superior thermal stability. Owing to these properties, they have gained significant attention for applications in construction materials, fire-resistant structures, and advanced structural components [13].

Table 4 Summary of fly ash research areas

Research Category	Key Research Focus and Latest Trends	Key Findings/Impact
High-Volume Fly Ash (HVFA) [14]	Developing binders with >70% fly ash content (Ultra-HVFA) to replace Portland cement.	Reduces CO_2 emissions by up to 80%; uses nano-silica (1–4%) to offset low early-age strength.
Material Classification [15]	Refining Class F (low-calcium) vs. Class C (high-calcium) categories based on specific mineralogy.	Fly ash properties vary by power plant, requiring site-specific mix designs for optimal performance.
Geopolymer Technology [16]	Activating fly ash with alkaline solutions or lime to create clinker-free cement.	Provides superior chemical resistance to sulfates and acids; enables "zero-clinker" cement production.
Agricultural Utility [16]	Using fly ash as a soil conditioner to improve texture and provide micro/macro nutrients (Fe, Zn, K, P).	Increases plant biomass by 11.6–29.2% at low application rates (<25%); neutralizes acidic soils.
Advanced Manufacturing [17]	Incorporating fly ash into ceramics, metal matrix composites (MMCs), and polymer wood substitutes.	Ceramic tiles made with 60% fly ash show reduced firing shrinkage and higher abrasion resistance.
Environmental Remediation [18]	Using fly ash-derived zeolites as adsorbents for heavy metals and flue gas treatment.	Reaches adsorption capacity of ~150 mg/g for heavy metals; helps in wastewater remediation.

4.3 Polymer Composites Reinforced with Fly Ash

Fly ash is also increasingly utilized as a reinforcing filler in polymer composites. When incorporated into polymer matrices such as epoxy, polyethylene, or polypropylene, fly ash enhances the overall mechanical and thermal performance of the composite materials. The addition of fly ash can improve tensile strength, increase hardness, and enhance wear resistance, while simultaneously reducing the overall cost of polymer production. Consequently, fly ash-reinforced polymer composites are considered promising materials for various engineering and industrial applications [14].

4.4 Fly Ash Derived Nanomaterials

Fly ash can serve as a precursor for synthesizing various nanomaterials including silica nanoparticles, zeolites, alumina nanoparticles, and carbon-based nanostructures. These nanomaterials demonstrate unique properties such as high catalytic activity, adsorption capacity, and electrical conductivity. Applications include catalysis, environmental remediation, sensors, and biomedical technologies [15].

4.5 Fly Ash Utilization

Fly ash-based smart materials have diverse applications. Fly ash is used in high-performance concrete, geopolymer cement, and self-healing construction materials. Fly ash composites combined with conductive fillers can absorb electromagnetic radiation and protect electronic devices. Fly ash-derived materials are used for adsorption of heavy metals, dyes, and pollutants from wastewater. Recent research explores the use of fly ash-based composites in thermal energy storage systems and battery electrode materials (Table 4) [16].

5. Characterization Techniques

5.1 X-Ray Diffraction (XRD)

Various analytical techniques are used to evaluate fly ash-based smart materials. X-ray diffraction (XRD) is a widely used analytical technique for the qualitative identification of crystalline phases present in fly ash. In this technique, a beam of X-rays is directed onto the solid sample. When the X-rays interact with the atoms in the crystal lattice, they are scattered or diffracted depending on the arrangement of atoms within the material. The diffraction occurs according to the crystallographic structure of the sample, producing characteristic diffraction patterns. Some X-rays are diffracted by the ordered crystalline regions, while others may penetrate deeper into the sample before interacting with internal crystal planes. During analysis, the XRD instrument scans a range of diffraction angles (2θ) and records the intensity of the scattered X-rays. The resulting data are plotted as a diffractogram, which represents the relationship between the diffraction angle and the diffracted intensity. This pattern is then used to identify the crystalline phases present in the fly ash sample [17].

5.2 X-Ray Fluorescence (XRF)

X-ray fluorescence (XRF) is widely used to determine the bulk oxide composition of different types of fly ash. This technique provides both qualitative and quantitative information about the elemental and oxide constituents present in the sample. In addition, XRF analysis is often used to estimate the amorphous phase content by subtracting the crystalline phase content (obtained from XRD analysis) from the total oxide composition measured by XRF. In this technique, the fly ash sample is irradiated with high-energy primary X-rays. The interaction of these X-rays with the atoms in the sample causes the emission of characteristic fluorescent or secondary X-rays. These emitted X-rays are detected and analyzed to identify and quantify the oxide components present in the fly ash. Thus, XRF serves as an effective method for both qualitative and quantitative determination of the chemical composition of fly ash [16,17].

5.3 Particle Size Distribution

Laser diffraction is commonly used to determine the particle size distribution of fly ash (FA). This technique employs a laser beam to analyze the size distribution of FA particles as well as other types of particulate samples. When the laser beam passes through the sample, it interacts with the particles and causes light scattering. This scattering occurs due to diffraction, refraction, and reflection of the light by the particles, while a portion of the light may also be absorbed. The instrument measures the pattern and intensity of the scattered light produced by the interaction between the particles and the laser beam. These scattering patterns are then analyzed using mathematical models based on either the Fraunhofer or Mie theory to calculate the particle size distribution. In the instrument, the diffracted light is collected and focused by a Fourier transform lens, which converts the incident light energy into electrical signals for analysis. The particle size is determined based on the angle between the incident and the scattered (diffracted) light; smaller particles scatter light at larger angles, while larger particles scatter light at smaller angles [18].

5.4 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is widely used to examine the morphology and microstructure of fly ash (FA), particularly to study its amorphous phase composition. In SEM analysis, a focused electron beam is directed onto the sample surface and penetrates to a depth of approximately 1 μm. The interaction of the electron beam with the sample generates various signals that are detected and converted into intensity data to produce a high-resolution image on a computer screen.

In secondary electron imaging, the signals generated provide detailed information about the surface topography of the sample. These signals are produced when the incident electron beam interacts with the atoms of the material and ejects valence electrons from the surface. The emitted electrons are collected by a detector, and the resulting signal intensity is proportional to the number of electrons detected, which is then used to form the SEM image [19].

An Energy Dispersive X-ray Analyzer (EDXA or EDX) is often coupled with SEM to determine the elemental composition of the particles. When the electron beam strikes the specimen surface, characteristic X-rays are emitted from the atoms in the sample. These X-rays are analyzed using specialized computer software to identify and quantify the elemental composition of the amorphous particles.

The amorphous particles in fly ash are typically spherical in shape, with diameters ranging from about 1 to 5 μm. A built-in measuring tool in the SEM system is used to determine the particle size, and only particles within this size range are selected for EDX point analysis. In addition, larger particles in the range of 150–200 μm may also be analyzed to obtain a more comprehensive understanding of the fly ash composition [20].

The quantitative analysis generally focuses on eight major elements: iron (Fe), oxygen (O), calcium (Ca), aluminum (Al), potassium (K), sodium (Na), carbon (C), and silicon (Si). These elemental compositions are subsequently converted into their corresponding oxide forms, and each analysis point is plotted on a ternary diagram for further interpretation of the chemical characteristics of the fly ash sample.

6. Environmental Benefits and Utilization of Fly Ash in Advanced Materials

The utilization of fly ash in advanced and smart materials offers significant environmental, economic, and technological benefits. Fly ash, a by-product generated from coal combustion in thermal power plants, is produced in enormous quantities worldwide. If not properly managed, large volumes of fly ash are disposed of in landfills or ash ponds, which can lead to land degradation, groundwater contamination, and air pollution. Therefore, the effective utilization of fly ash in advanced materials provides an environmentally sustainable solution for waste management (Table 5) [21]. One of the major advantages of fly ash utilization is the reduction of industrial waste disposal. By incorporating fly ash into construction materials, nanocomposites, geopolymers, ceramics, and other smart materials, the amount of waste sent to landfills is significantly decreased. This not only minimizes environmental pollution but also reduces the need for large ash disposal areas. Additionally, the use of fly ash helps conserve natural resources such as limestone, clay, and sand, which are used as raw materials in conventional material production [22].

Table 5 Quantified environmental benefits of fly ash [19-21]

Environmental Factor	Impact of Fly Ash Utilization	Statistics & Research Findings
Carbon Emissions	Replaces carbon-intensive Ordinary Portland Cement (OPC).	Every 1 tonne of cement replaced by fly ash saves ~0.85–1.0 tonnes of CO_2 emissions.
Energy Conservation	Eliminates the need for high-temperature kiln firing required for clay bricks and cement clinker.	Fly ash bricks consume 10–15 times less energy than traditional burnt clay bricks.
Natural Resource Protection	Reduces the depletion of fertile topsoil used for red bricks and limestone for cement.	Saves significant volumes of valuable topsoil; replacing 1–2% of clay bricks with fly ash versions saves 0.5–1.5 million tons of soil annually.
Water Conservation	Lowers the water-to-cement ratio and reduces soaking requirements.	Fly ash AAC blocks use significantly less water during production and installation compared to red bricks.
Waste Management	Diverts industrial waste from landfills and ash ponds.	Repurposing fly ash prevents the leaching of heavy metals (like arsenic and boron) into the groundwater table from unlined landfills.
Agricultural Soil Health	Acts as a soil conditioner and nutrient supplier for degraded lands.	Increases soil pH in acidic soils and provides micro/macro nutrients (Fe, Zn, K, P).

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Fly ash-based materials also contribute to the reduction of carbon dioxide (CO_2) emissions. In the construction industry, replacing a portion of cement with fly ash lowers the demand for Portland cement production, which is one of the major sources of global CO_2 emissions. The partial substitution of cement with fly ash can therefore significantly reduce the carbon footprint of construction activities while maintaining or even improving the mechanical and durability properties of final products [23].

Furthermore, fly ash possesses unique physicochemical properties such as fine particle size, spherical morphology, high silica and alumina content, and pozzolanic activity.

These characteristics make it highly suitable for the development of advanced materials including geopolymer binders, polymer composites, catalysts, adsorbents, and nano-structured materials. Such applications enhance material performance in terms of strength, durability, thermal stability, and chemical resistance [24].

The transformation of waste fly ash into value-added smart materials also supports the principles of the circular economy. Instead of being treated as waste, fly ash is converted into a valuable secondary raw material that can be reused in various industrial applications [25]. This approach promotes sustainable resource management, reduces environmental impacts, and supports global sustainability goals related to waste reduction, resource efficiency, and climate change mitigation [26].

Overall, the utilization of fly ash in advanced materials not only provides an effective solution for waste management but also contributes to sustainable industrial development and environmental safety [27, 28].

7. Challenges in the Utilization of Fly Ash for Smart Materials

Although fly ash offers numerous advantages for the development of advanced and smart materials, several challenges still limit its large-scale and consistent utilization. One of the major issues is the variability in the chemical composition of fly ash [29].

The composition of fly ash depends largely on the type of coal used, combustion conditions, and the design of the power plant. As a result, the proportions of major oxides such as silica, alumina, calcium oxide, and iron oxide can vary significantly, which may affect the performance and reliability of fly ash-based materials [30, 31].

Another concern is the presence of trace toxic elements in fly ash. Elements such as arsenic, lead, mercury, and chromium may be present in small amounts and could pose environmental or health risks if not properly stabilized or encapsulated within the material matrix. Therefore, careful characterization and treatment of fly ash are necessary before its use in advanced material applications [32, 33].

Limited compatibility with certain polymers is also a challenge when fly ash is used as a reinforcing or filler material in polymer composites. Poor interfacial bonding between fly ash particles and the polymer matrix can reduce the mechanical strength and overall performance of the composite material [34]. Surface modification or chemical treatment of fly ash particles is often required to improve compatibility and dispersion within polymer systems [35].

In addition, the development of high-performance fly ash-based smart materials often requires advanced processing techniques, specialized equipment, and precise control of synthesis conditions [36]. These requirements can increase production costs and limit large-scale industrial implementation.

To overcome these challenges, further research is required to improve material processing techniques, enhance fly ash modification methods, and develop standardized guidelines for its utilization [37]. Establishing proper quality control and standardization procedures will help ensure the consistent performance and broader application of fly ash in smart material development [38].

Future research on fly ash smart materials focuses on nano-engineered composites, graphene-reinforced materials, and multifunctional responsive systems. Integration with sensor technologies, energy harvesting devices, and environmental monitoring systems could further expand applications.

Advances in nanotechnology, materials science, and waste management will enable efficient utilization of fly ash for next-generation smart materials [39].

8. Conclusion

Fly ash is a valuable industrial by-product with immense potential for developing smart and functional materials. Its chemical composition, availability, and economic advantages make it an attractive alternative to conventional raw materials. The development of fly ash-based geopolymers, nanomaterials, and polymer composites demonstrates significant progress toward sustainable material innovation. Continued research and technological advancements will further enhance the role of fly ash in smart materials and contribute to sustainable industrial development.

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