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REVIEW PAPER

Electrochemical applications of fly ash as surface modifier: sustainable mitigation of industrial residue

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Abstract
The conversion of byproduct fly ash into beneficial materials has garnered significant attention over the years. Due to its unique properties, fly ash is widely utilized to modify the surface of carbon materials, enhancing porosity, conductivity, surface area, lithium storage capacity, cycling stability, and providing additional redox activity. It is also employed in electrocatalytic reactions (e.g., HER and ORR), galvanization, electrocoagulation of heavy metal pollutants, and as a composite cement filler. Recent findings suggest fly ash-integrated materials and surfaces significantly improve early-age mechanical strength and delay deformation. However, there are only a few reports explaining this aspect. This review discusses the electrochemical and physicochemical properties of fly ash and its role as a surface-modifying substance on an industrial scale.

Keywords Fly ash · Functionalization · Dye-sensitized solar cells · Anticorrosion coatings · Electrochemical applications

Introduction

Fly ash is a fine, powdery residue left over from burning pulverized coal in power plants. It is carried out of the boiler with flue gases and collected using electrostatic precipitators or bag filters before being released into the atmosphere [1, 2]. Fly ash consists primarily of inorganic minerals and is known for its pozzolanic properties, making it useful in various applications, including construction, environmental management, and electrochemical devices. It primarily consists of oxides of silicon, iron, calcium, and aluminum, along with smaller amounts of other elements such as magnesium, potassium, sodium, and sulfur [3–6]. The exact composition can vary depending on the type of coal burned. Fly ash exhibits variable electrical conductivity, meaning its ability to conduct electricity can differ based on several factors. The specific elements present in the fly ash, particularly the number of conductive oxides like iron oxides, influence conductivity. Smaller and more spherical particles tend to offer better conductivity due to increased contact points between particles [7–9]. Fly ash readily absorbs moisture, and water conducts electricity. So, the amount of moisture content can significantly impact conductivity [11–16]. Fly ash with some degree of sintering might exhibit higher conductivity due to improved particle connections [17–20].

Bibliometric analysis reveals that studies on the sustainable mitigation of fly ash as a surface modifier have grown steadily since 1990, with an average annual growth rate of 10.5% [21–23]. The number of related articles rose from 9 in 1989 to 135 in 2023, non-linearly. In the last decade (2010–2019), 1400 articles were published, constituting 69.01% of the total publications on fly ash applications during 2000–2019. This number of articles indicates the rapid expansion of fly ash mitigation research after 2010 (Fig. 1). The percentage contribution of publications per year is also shown in Fig. 1. The average number of publications over 20 years is 54 articles per year. The annual publication rate has increased consistently over the last 10 years (2014–2023), demonstrating high recent activity in fly ash alleviation research [21–23]. The retrieved literature shows successful applications of fly ash as a surface-modifying agent in various material science applications, including efficient battery and supercapacitor materials and electrochemical sensors. This review discusses the detailed properties of fly ash and its practical electrochemical

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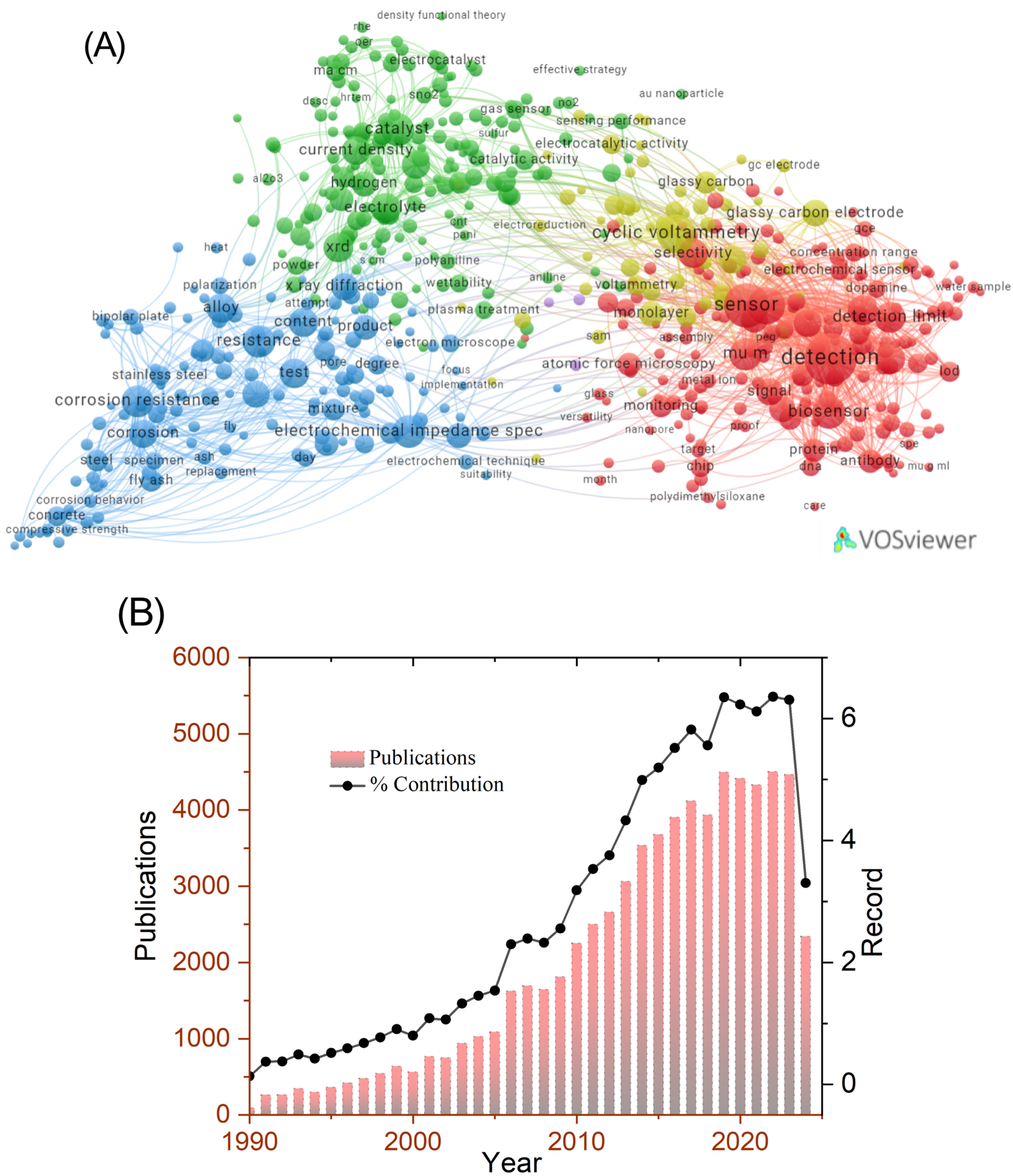

Fig. 1 **A** Distribution of topic wise research in fly ash field using VOS viewer. **B** Growth of literature related to electrochemical mitigation of fly ash studies, 1990–2024

utilization. Additionally, the systematic review approach includes discussion on the environmental impact associated with fly ash and the importance of mitigation, quantitative assessment of sustainable improvements and major findings, technological advancements, and challenges in electrochemical usage.

Environmental impact of fly ash and the importance of mitigation

This byproduct has several harmful environmental impacts if not properly managed [24–29]. Major concerns include air and water pollution, soil contamination, wildlife and ecosystem damage, human health risks, and visual impacts. Fly ash can become airborne as particulate matter, contributing to air pollution. Inhalation of fine particles can cause respiratory problems, cardiovascular diseases, and other health issues. Fly ash may contain harmful substances like heavy metals (e.g., lead, arsenic, and mercury) and radioactive elements, which can be released into the air, posing significant health risks. Water bodies are polluted with fly ash through leaching and surface water contamination. When fly ash is disposed of in landfills or storage ponds, heavy metals and other toxic substances can leach into groundwater, contaminating drinking water sources and affecting aquatic life [24–26].

Runoff from fly ash disposal sites can carry pollutants into nearby rivers, lakes, and streams, leading to the contamination of surface water bodies [27–29]. Soil strata can be polluted by fly ash disposal, leading to the accumulation of toxic elements in the soil. These elements can be absorbed by plants, entering the food chain and affecting ecosystems. Fly ash can alter soil pH and structure, potentially affecting soil fertility and plant health. Fly ash disposal sites can disrupt natural habitats, affecting wildlife and plant species. Contaminated water and soil can harm terrestrial and aquatic ecosystems. Toxic substances from fly ash can bioaccumulate in organisms, leading to higher concentrations of these toxins in predators and posing long-term ecological risks. Exposure to fly ash dust can cause respiratory problems, including asthma, bronchitis, and other chronic lung diseases [27–29]. Long-term exposure to heavy metals found in fly ash can lead to severe health issues, including neurological damage, kidney failure, and cancer. Fly ash can contain trace amounts of radioactive elements, posing radiation risks to humans and animals. Fly ash disposal sites can be unsightly, affecting the visual landscape and reducing the aesthetic value of an area. Fly ash can also generate unpleasant odors and dust, causing discomfort and health issues for nearby communities [27].

Finding beneficial uses for fly ash is of paramount importance due to its significant environmental, economic, and societal benefits [30–35]. By repurposing this byproduct, industries can reduce waste, conserve natural resources, lower costs, and promote sustainability. Moreover, utilizing fly ash in construction and other applications can enhance material properties and contribute to infrastructure development, supporting overall economic growth [30–32]. Major environmental benefits include waste reduction and resource conservation. Fly ash can minimize landfill use, conserving valuable landfill space and mitigating associated environmental issues such as leaching and groundwater contamination. This process can lower the release of injurious substances into the air, water, and soil, thereby protecting ecosystems and human health. Using fly ash in place of natural materials (e.g., sand, gravel, and cement) can conserve these finite resources and reduce the environmental impact of their extraction and processing. Economic benefits, such as cost savings and market development, ensure the availability of cost-effective raw material alternatives for various industrial applications. Companies can reduce costs associated with waste disposal and landfilling. Innovative uses of fly ash can lead to the development of new products and markets, creating economic opportunities and fostering industrial growth [30–35]. The recycling and processing of fly ash can also create jobs in manufacturing, construction, and environmental management sectors. Utilizing fly ash supports sustainable development goals through reducing environmental impacts, conserving resources, and promoting economic growth. As a construction material, fly ash enhances the properties of concrete, such as increasing its strength, durability, and workability. This results in longer-lasting structures and reduced maintenance costs. Fly ash can be used in various construction materials, including bricks, blocks, and tiles, providing versatile and high-performance building solutions. The use of fly ash in construction projects can lower material costs and improve project affordability, aiding in infrastructure development, particularly in developing regions. Using fly ash in environmentally beneficial ways helps industries comply with environmental regulations and standards, avoiding potential fines and penalties. Research into new uses for fly ash can lead to innovative applications and technologies, driving scientific and technological advancements [34–37].

Quantitative assessment of sustainable improvement

Several techniques are employed to optimize the performance of fly ash as a surface modifier. Fly ash-based modification typically occurs through physical and chemical pathways. Physical methods such as grinding reduce particle size to enhance surface area and reactivity, while the calcination process involves heating fly ash to modify its material properties [35–39]. Chemical procedures involve treatment with acid and alkaline solutions to remove impurities, increase reactivity, and enhance pozzolanic activity. Treatment with coupling agents improves compatibility between fly ash and the polymer matrix. Recent studies indicate that using fly ash as a surface modification material can mitigate its harmful environmental effects. The degree of sustainability can be evaluated through processes such as Life Cycle Assessment (LCA), assessing resource depletion, energy consumption, and greenhouse gas emissions. A detailed quantitative assessment of potential sustainability improvements associated with using fly ash involves evaluating its environmental, economic, and social impacts.

Key metrics have been explored, including the substitution of fly ash for Portland cement in concrete to significantly reduce CO_2 emissions. For every ton of cement replaced by fly ash, approximately 0.8 tons of CO_2 emissions can be avoided [35–38]. Quantitatively, if 100 million tons of fly ash are used annually, CO_2 emissions could be reduced by 80 million tons. Second, using fly ash in supercapacitors and battery electrodes reduces the need for energy-intensive raw materials like graphite and silicon. Mathematically, replacing 10% of electrode materials with fly ash can reduce overall material production energy by approximately 5–10%, leading to a corresponding reduction in CO_2 emissions. Third, utilizing fly ash reduces the burden on landfills and associated environmental hazards. Globally, approximately 750 million tons of fly ash are generated annually. If 50% of this production is utilized in various applications, 375 million tons of waste could be diverted from landfills annually. Fourth, considering economic impacts such as cost savings on construction materials and energy storage options, fly ash is often cheaper than traditional materials like Portland cement ($30 per ton versus $100 per ton). Substituting 50 million tons of cement with fly ash could save $3.5 billion annually. In addition, fly ash-based electrodes can be less expensive than conventional materials, potentially saving the industry millions of dollars annually based on production scale. Fifth, using fly ash reduces the need for quarrying and processing raw materials, which can decrease air and water pollution and have positive social impacts. A 10% reduction in particulate emissions in regions with heavy construction activity could potentially lower respiratory diseases by approximately 5% [38, 39].

Important case studies suggest that replacing 25% of cement with fly ash in the construction of a 1 million cubic meter dam saved 200,000 tons of CO_2. Research has shown that using fly ash in electrodes reduced material production energy by 8%, resulting in significant energy and cost savings in large-scale production. Additionally, fly ash-based anticorrosive coatings increased the lifespan of steel structures by 20%, reducing maintenance costs and material usage over time.

Ashfaq and Moghal estimated costs and carbon footprint analysis in two scenarios, particularly (I) FA-based embankment and (II) pavement that was constructed using FA as a sub-base material [38]. They observed that carbon emissions at the procurement stage were greater than at other stages, close to 77% and 74% share in total emissions at I and II. The carbon emission coefficient was insignificant < 1% for the site of operation in both scenarios. The haulage stage caused the maximum emissions for both I and II, as shown in Fig. 2A, B. The emissions at this stage were analyzed in terms of the type of vehicle (pickup truck and dumper), as mentioned in Fig. 2C, D. Tosti et al. investigated the technical properties and environmental functionality of blended cement mortar containing different replacement ratios of biomass fly ash. Three different types of FAs were taken for the study, with particle size < 1 mm. In Fig. 3, the release of the batch tests was provided for L/S 10 expressed as a percentage of the limit value of the SQD (open application) for all of the crushed mortars as well as the associated pure fly ash samples [39].

Physicochemical properties of fly ash as a modifier

Particle size and surface area

These are among the most fundamental parameters that significantly influence the properties and suitability of fly ash for various applications, including its use as a surface modifier in electrochemical systems. Fly ash particles have a broad size range, typically from below one micrometer to tens of micrometers [40–46]. Factors such as the type of coal, combustion conditions, and collection methods (including post-collection modifications) regulate the fly ash particle size distribution. Fly ash generally consists of both coarse and fine particles, with finer particles often dominating the overall distribution. Finer particles, typically those smaller than 100 microns, contribute significantly to the overall surface area of fly ash due to their high specific surface area. These fine particles are often more reactive and accessible, making them desirable for various applications where surface interactions, such as adsorption or catalysis, are critical. Coarser particles, with sizes greater than 100 microns, also affect the properties of fly ash (Fig. 4). While they contribute less to the overall surface area, they can influence factors such as porosity, packing density, and the mechanical characteristics of fly ash-based materials [40–46].

Chemical composition

When discussing the chemical composition of fly ash as a modifier in electrochemical applications, it is essential to consider how its composition affects its performance and interactions within these systems. While the exact

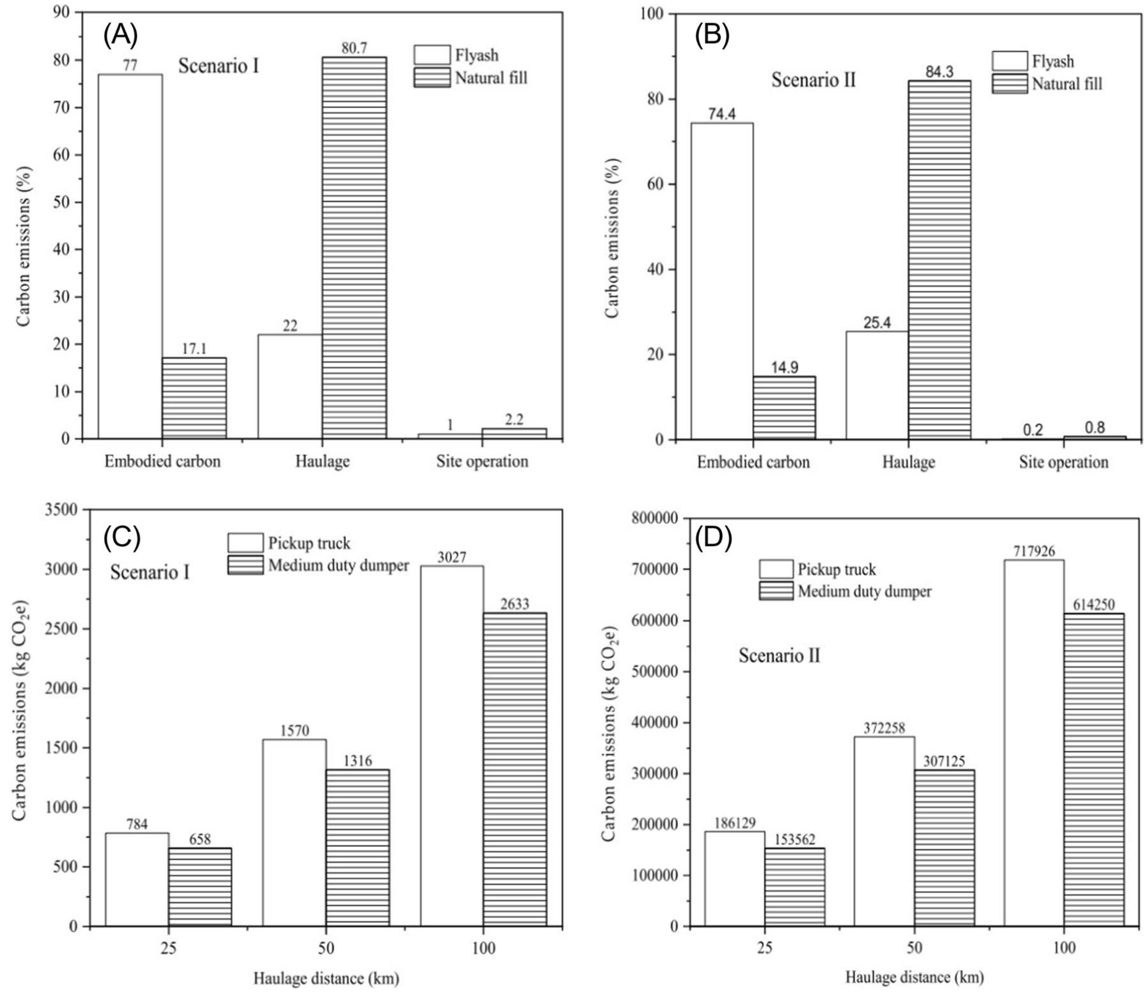

Fig. 2 **A**, **B** The carbon emissions versus the CFA stages for scenario I and scenario II, respectively. **C**, **D** The variation in emissions associated with vehicle type and haulage distance for scenario I and scenario II, respectively [38]

composition can vary based on factors such as the source of coal and combustion conditions, certain components play a crucial role in influencing its behavior as a modifier [48–52]. Understanding the chemical composition associated with fly ash is critical to tailoring its properties and optimizing its performance in electrochemical applications. Silica (SiO_2) is a major component of fly ash and contributes to its structural integrity. In electrochemical applications, SiO_2 can participate in surface interactions and adsorption processes and provide stability to modified electrodes. Alumina (Al_2O_3) is another significant constituent of fly ash. It can enhance the surface reactivity and stability of fly ash-modified electrodes, influencing processes such as electron transfer and catalytic activity. Iron oxide (Fe_2O_3) present in fly ash can act as a redox-active species, facilitating electron transfer processes in electrochemical reactions, and may also contribute to the catalytic properties of fly ash-modified electrodes. Calcium oxide (CaO) can influence the pH buffering capacity of fly ash-modified electrodes and may participate in reactions involving alkaline species. It can also contribute to the structural stability of modified electrode materials. Depending on combustion conditions, fly ash may also contain carbonaceous material, which can impart electrical conductivity to modified electrodes. Carbonaceous components can enhance the electrochemical performance of fly ash-modified electrodes, particularly in applications requiring high conductivity. Additionally, fly ash may contain trace amounts of various elements, including transition metals and metalloids [1–9, 49–52]. These trace elements can affect the catalytic activity, selectivity, and stability of fly ash-modified electrodes in electrochemical reactions.

Porosity and surface morphology

Porosity and surface morphology are critical properties of fly ash when used as a modifier in various applications, including electrochemical systems [53–57]. Fly ash typically exhibits intrinsic porosity due to the presence of voids and pores

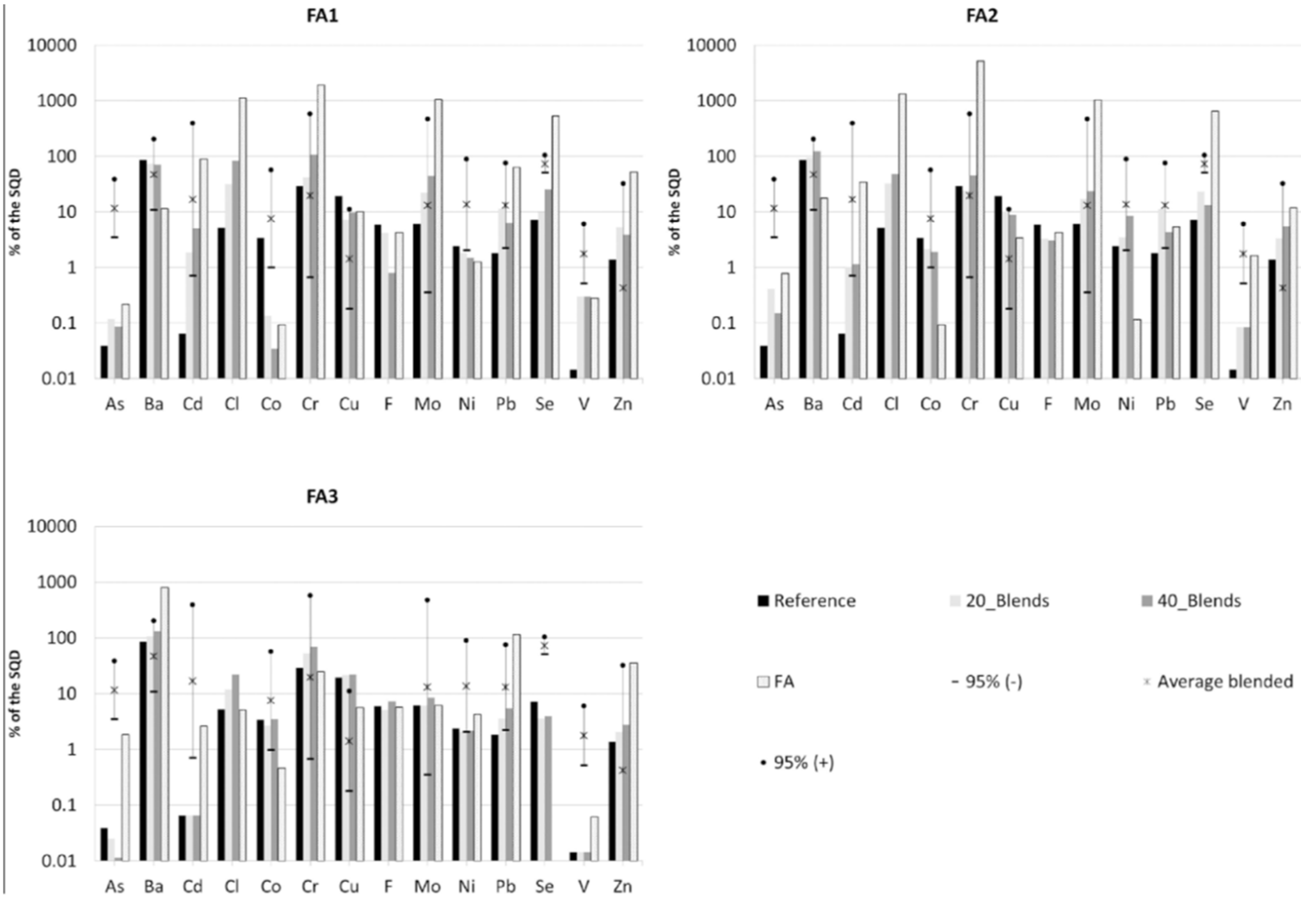

Fig. 3 Release of the batch tests that involved crushed cement mortars and the corresponding pure fly ash material at L/S 10 and under natural pH [39]

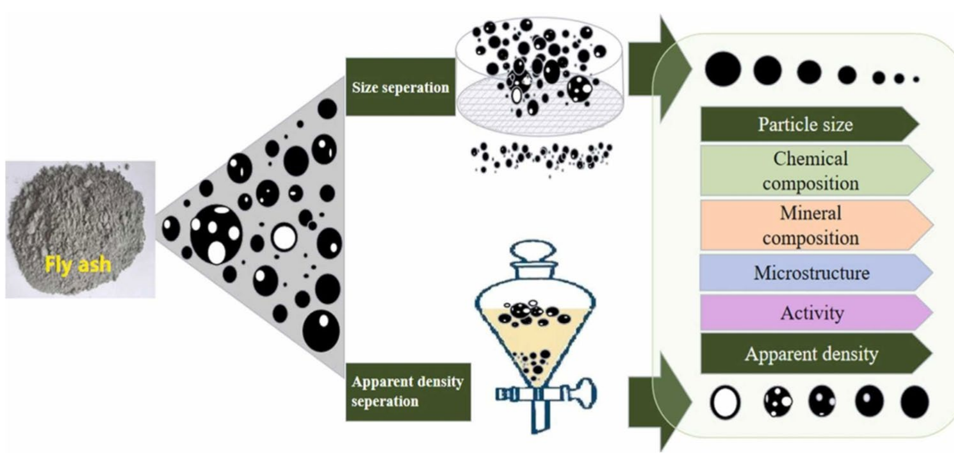

Fig. 4 Schematic showing the correlation between the sorting indices and the characteristics of fly ash [47]

within its structure. This porosity arises from various factors, including the combustion process, the mineral content of the coal, and the subsequent cooling and solidification of molten ash particles. Porosity contributes to the effective surface area of fly ash, enhancing its interaction with electrolytes or reactants in electrochemical systems [53–57]. Higher porosity provides more sites for adsorption, chemical reactions, and ion exchange processes, which can be advantageous in applications such as electrode modification and catalysis. Porous structures facilitate ion transport within the material, enabling the rapid diffusion of ions to active sites on the surface. This property is crucial for applications where efficient mass transport is essential, such as in supercapacitors, batteries, and electrochemical sensors. Porous fly ash structures allow electrolytes to penetrate the material, ensuring intimate contact between the modifier and the electrolyte. This approach enhances the efficiency of electrochemical processes by reducing interfacial resistance and facilitating charge transfer at the electrode–electrolyte interface. Fly ash particles typically exhibit irregular surface morphology characterized by roughness, cracks, crevices, and other surface features. These irregularities increase the effective surface area available for electrochemical reactions and enhance the accessibility of active sites. Surface morphology influences the distribution of active sites on the fly ash surface, which can vary depending on factors such as particle size, particle shape, and composition [53–57]. Surface defects, edges, and surface functional groups serve as preferred sites for adsorption, catalysis, and electron transfer reactions in electrochemical systems. Surface morphology plays a crucial role in the modification of electrodes with fly ash. The rough and porous surface of fly ash particles provides anchoring sites for electrode materials, facilitating the deposition and immobilization of active species or catalysts onto the electrode surface. Surface morphology affects the reactivity of fly ash as a modifier, influencing its catalytic activity, adsorption capacity, and electrochemical performance [56, 57]. Irregular surface features promote enhanced reactivity by providing more opportunities for surface interactions and electrochemical reactions. In summary, the porosity and surface morphology of fly ash significantly impact its effectiveness as a modifier in electrochemical applications.

Surface functional groups

Surface functional groups (-OH, -COOH, $-NH_2$, and $-PO_4H_2$) on fly ash play a crucial role in its performance as a modifier in various applications, including electrochemical systems. These functional groups are chemical moieties present on the surface of fly ash particles that interact with other substances, such as electrolytes, ions, or molecules, thereby influencing the material properties and behavior [58–63]. Hydroxyl groups (-OH) are frequently present on the surface of fly ash particles, originating from the hydroxylation of metal oxides (e.g., Si–OH, Al–OH, and Fe-OH) or from the adsorption of water molecules. Hydroxyl groups can enhance the wettability and dispersibility of fly ash in aqueous solutions, facilitating its incorporation into electrode materials or catalyst supports. Carboxyl groups (-COOH) may be present on the surface of fly ash due to the oxidation of organic matter during combustion or from the adsorption of atmospheric carbon dioxide. These functional groups can serve as anchoring sites for functionalization or surface modification, allowing for the introduction of specific chemical functionalities or the attachment of desired molecules. Silanol groups (-SiOH) arise from the hydrolysis of siloxane bonds present in the silica-rich phases of fly ash particles (e.g., Si–O-Si). Silanol groups can facilitate the immobilization of functional materials or nanoparticles onto the fly ash surface, enhancing its performance as a modifier in catalysis, sensing, or electrode applications. Amine groups ($-NH_2$) may be introduced onto the surface of fly ash through chemical modification or functionalization reactions [58–63]. These functional groups can impart basicity to the surface of fly ash and enhance its affinity for acidic species or metal ions through complexation or ion exchange processes. Phosphate groups ($-PO_4H_2$) can be present on the surface of fly ash due to interactions with phosphorus-containing species during combustion or post-combustion treatments. Surface functional groups on fly ash enable tailored modifications to enhance its performance in specific applications, including electrochemical systems.

Thermal stability

The thermal stability of fly ash is an important consideration when it is used as a modifier in various applications, including those involving high-temperature processes or environments. Thermal stability refers to the capability of a material to maintain its structural integrity, chemical composition, and functional properties under elevated temperatures [64–69]. The mineral constituents of fly ash, such as alumina (Al_2O_3), silica (SiO_2), and iron oxide (Fe_2O_3), exhibit high melting points and resistance to thermal decomposition, contributing to the overall thermal stability of fly ash. While fly ash is thermally stable under typical operating conditions, certain transformations or reactions may occur at higher temperatures. Additionally, the presence of crystalline phases such as mullite, gehlenite, or hematite in fly ash can influence its thermal behavior and stability. Thermal treatment of fly ash can induce chemical reactions or transformations, such as carbonization of organic matter, oxidation of metal sulfides, or formation of new mineral phases [64–69]. Despite its thermal stability, the performance of fly ash as a modifier may be influenced by the specific application conditions. For example, in applications involving high-temperature processes such as thermal energy storage, catalysis, or refractory materials, the thermal stability of fly ash becomes critical. Processes such as sintering, heat treatment, or thermal annealing may be employed to enhance the performance of fly ash-based materials, requiring careful consideration of the thermal behavior and stability. In summary, fly ash exhibits good thermal stability, making it suitable for use as a modifier in various applications, including those involving high-temperature environments or processes [64–69].

Utilization of fly ash for electrochemical purposes

Electrocatalysis

Owing to the presence of various oxides (such as silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3)) and unburned carbon, fly ash shows potential to be a valuable resource for catalytic applications. The advantages of using fly ash in electrocatalysis include its abundance and low cost, its role in managing and recycling industrial waste, its contribution to a circular economy, and the creation of catalysts with desirable properties. Recent studies have concluded that utilizing fly ash as a composite material can improve the stability and the electrocatalytic properties of the material. Although fly ash has not been extensively utilized for electrochemical purposes, several investigations have revealed its efficient use as an electrocatalyst [70–78]. Kanjana et al. explored the use of fly ash mixed with PEDOT (FP) to create a new type of counter electrode for dye-sensitized solar cells (DSSCs) [70]. The FP film acts as both a catalyst and binder, with the fly ash increasing the number of active sites. The research demonstrates that the performance of DSSCs made from FP films can be optimized by adjusting the amount of fly ash incorporated. A 2:5 g/mL fly ash to PEDOT ratio achieved high efficiency comparable to platinum counter electrodes, highlighting the potential of fly ash for efficient and sustainable solar cell technology. Similarly, Thirumalai et al. discovered that adding fly ash to zinc oxide creates a more effective material for driving chemical reactions with higher electrocatalytic activity. The composite material demonstrated better electrochemical stability because the fly ash increases the surface area available for these reactions [71]. A study by Altalhi et al. found that combining fly ash with titanium dioxide nanoparticles (TiO_2) creates a highly effective material (FA-TiO_2) for producing hydrogen fuel through the hydrogen evolution reaction (HER) in alkaline solutions. This improvement is due to the FA-TiO_2 catalyst having more active sites for the reaction [72]. Maiaugree et al. created a counter electrode for solar cells by mixing titanium dioxide nanoparticles (TiO_2) with a conductive polymer (PEDOT). This design achieved high efficiency (8.49%), close to that of expensive platinum electrodes (7.50%). The success of this design was due to the tiny TiO_2 particles increasing the surface area of the polymer, allowing for more efficient chemical reactions within the electrode [73].

Lim et al. describe an alternative method for producing zeolites X and A [74]. Their approach involved treating non-magnetic fly ash (FA) with acetic acid for different time intervals (7 and 12 h). The resulting zeolites, named, zeolite-XF7, zeolite-XF12, and zeolite-X&AF, depending on the treatment time, were then used in dye-sensitized solar cells (DSSCs) with quasi-solid-state electrolytes (Fig. 5). This application evaluated enhancing the efficiency of these solar cells by incorporating zeolites. The research by Alluqmani et al. utilized titania/carbon derived from carbonaceous oil fly ash (COFA) to create carbon nanostructures with a large surface area. They achieved this through a green and

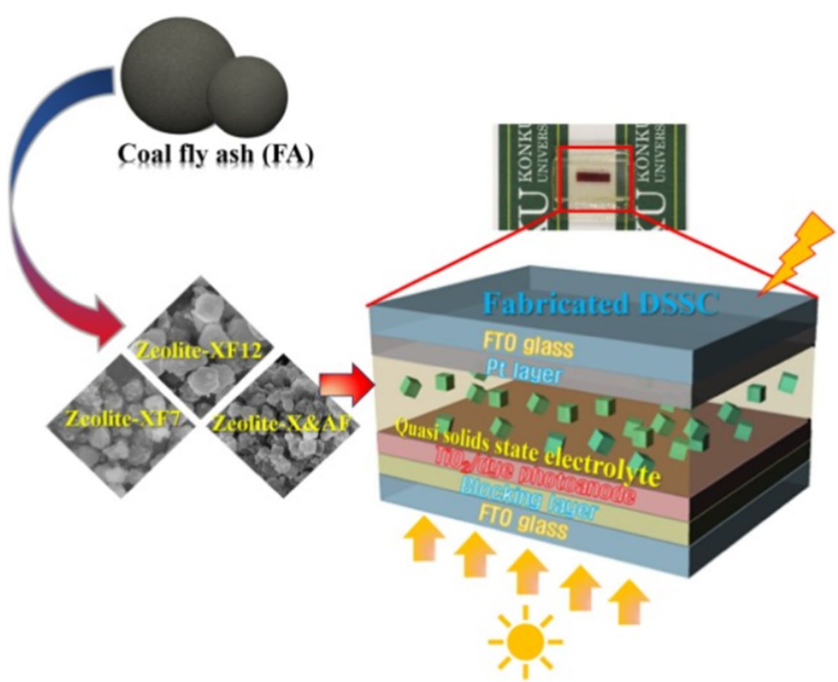

Fig. 5 Schematic showing the DSSCs with quasi-solid-state electrolytes [74]

cost-effective method called ball milling. The team then investigated the properties of thin films made from titanium dioxide (TiO_2) and COFA deposited on glass at low temperatures (below 500 °C). This investigation explored the potential application of the film in dye-sensitized solar cells (DSSCs) [75]. Nunes et al. explored coal fly ash as a potential replacement for natural graphite in critical clean energy technology: oxygen reduction reaction (ORR) electrocatalysts [76]. These electrocatalysts play a vital role in fuel cells. In a previous study, Fernandes et al. investigated the catalytic activity of coal char for ORR applications. However, they found that a graphitization approach did not enhance the performance of the char. Consequently, the researchers aim to develop a method to enrich the carbon content in fly ash through simple separation techniques like sieving and magnetic separation. This enriched carbon material could be used as an ORR electrocatalyst [77].

Patti et al. developed innovative biochar-supported copper tungstate nanocomposites (Bio-$CuWO_4$ NCs) that function as visible light-active photocatalysts for degrading the drug ciprofloxacin (CF) and as electrocatalysts for methanol oxidation. These Bio-$CuWO_4$ NCs were synthesized using a simple hydrothermal approach. Brunauer–Emmett–Teller (BET) measurements showed that Bio-$CuWO_4$ NCs have a higher active surface area when compared to pristine biochar. UV–visible spectroscopy results indicated that Bio-$CuWO_4$ NCs can degrade up to 97% of CF in aqueous suspension after 90 min of visible light irradiation while maintaining good levels of repeatability and stability. Additionally, Bio-$CuWO_4$ NCs exhibited a higher peak current in methanol oxidation reactions [78].

Anticorrosion coatings

Utilizing fly ash for anticorrosion coatings is an innovative approach that leverages the unique properties of this industrial by-product to enhance the durability and performance of protective coatings. Fly ash can improve the barrier properties of coatings by filling micro-pores and voids in the coating matrix, thus reducing the permeability of corrosive agents like water, oxygen, and salts. Its incorporation can also enhance the mechanical strength and abrasion resistance of the coating, providing better protection against physical damage. Moreover, fly ash is a low-cost material compared to traditional anticorrosion additives, making the coatings more economical. Fly ash-based coatings have been applied to steel structures, such as bridges, pipelines, and storage tanks, to prevent rust and corrosion. These coatings are particularly useful in marine environments where structures are exposed to harsh, corrosive conditions. Machinery and equipment in industries operating under corrosive conditions can also benefit from fly ash-enhanced anticorrosion coatings. Typically, fly ash is blended with other materials like polymers, resins, and various additives to enhance its adhesion, durability, and protective properties. The performance of these coatings is evaluated based on criteria such as adhesion strength, corrosion resistance, durability, and thermal stability.

Recent studies have focused on optimizing the particle size distribution of fly ash, improving surface treatment methods to enhance compatibility with the coating matrix, and developing hybrid coatings that combine fly ash with nanomaterials for superior performance [58, 79–81]. Researchers led by Wang et al. designed a new protective coating of fly ash combined with polyalanine and iron ions (FA-PANI-Fe-F) for metals, offering both shielding and corrosion inhibition characteristics. This "bifunctional" design incorporates perfluorinated groups to repel water and iron ions (Fe^{2+}/Fe^{3+}) to form a protective layer on the metal surface. Tests showed that the coating significantly improves corrosion resistance. The perfluorinated groups enhance water repellency, while the iron ions provide both anodic protection and cathodic inhibition. This dual action creates a dense barrier between the coating and the metal, further preventing corrosion. Electrical impedance spectroscopy (EIS) confirmed the effectiveness of the coating, and a separate test (SVET) indicated that the iron ions effectively suppress corrosion in the cathode region. This research provides valuable insights into how coating protects metals and highlights its potential for long-lasting corrosion resistance [79].

Rooby et al. investigated a new type of protective coating for steel reinforcements using fly ash modified with nanoparticles. They compared five coatings: regular cement (CC), coal fly ash (CF), and fly ash combined with either nano-calcium carbonate (CFC), nano-silica (CFS), or nano-zirconia (CFZ). The researchers tested the performance of the coatings in chloride environments using electrochemical methods and long-term impressed voltage tests. They also analyzed the coating microstructure and corrosion products with several techniques. Results showed that coatings with nanoparticles (CFC, CFS, and CFZ) offered significantly lower corrosion rates compared to fly ash alone (CF). Accelerated tests revealed that incorporating nanoparticles delayed the onset of cracking in the coating. Among the nanoparticles, nano-zirconia (CFZ) performed best (Fig. 6). It exhibited better dispersion within the cement and minimal aggregation, leading to superior corrosion resistance, as confirmed by various tests; this translated to minimal rust formation and weight loss in CFZ-coated rebars during salt spray and chemical resistance tests. This study indicates the potential use of fly ash-based cementitious coatings containing nanoparticles, particularly nano-zirconia, for enhanced long-term corrosion protection of steel reinforcements in chloride-rich environments [80].

Chavana et al. studied the use of fly ash (FA) coatings for protecting marine-grade steel against erosion and corrosion.

Fig. 6 Photographs showing intense corrosion and wider cracks that were observed in uncoated rebars in comparison to coated ones [80]

They employed a design of experiments (DOE) approach to optimize the coating process. This method allowed them to efficiently identify cause-and-effect relationships between different processing parameters and the final coating properties using a minimal number of experiments. The study focused on three key parameters: sand particle size in the erosive slurry, slurry concentration, and rotational speed during coating application. The researchers analyzed the impact of these parameters on the performance of the coating via erosion tests and evaluated its corrosion resistance using a salt spray test. An additional electrochemical technique (impedance spectroscopy) further confirmed the corrosion protection effectiveness. Throughout the study, the performance of the FA coatings was compared to that of uncoated steel samples. This research emphasized the potential of fly ash for surface engineering applications, particularly in protecting marine-grade steel from erosion and corrosion damage in various industrial settings. The DOE approach demonstrated an efficient way to optimize the coating process for achieving the desired properties [81].

More et al. developed a new anticorrosion coating derived from sustainable resources. They created a polyester amide resin using palm oil, cured it with epoxy for added strength, and incorporated various elements to enhance its protective properties. The researchers included a composite material made of zinc oxide (ZnO), aluminum oxide (Al_2O_3), and fly ash. This composite was treated using a chemical (amino silane) to create bonding sites on its surface. Multi-walled carbon nanotubes (MWCNTs) were also introduced into the coating. These nanotubes underwent a separate treatment to form carboxyl groups on their surface, facilitating chemical bonding. By incorporating these treated materials (ZnO-Al_2O_3-fly ash composite and MWCNTs) into the polyester amide-epoxy resin, the researchers aimed to achieve both physical reinforcement and improved chemical adhesion within the coating. They also investigated the combined effect (synergistic effect) of using these elements together at varying concentrations. This study explored the potential of palm oil-based resins and strategically modified nanomaterials to create effective and sustainable anticorrosion coatings [58].

Supercapacitors and batteries

Exploiting fly ash for supercapacitors and battery applications is an emerging field that leverages the abundant availability and unique properties of this industrial by-product to enhance energy storage technologies. Fly ash, being rich in carbon, can be processed into activated carbon or carbon nanotubes, materials known for their excellent electrical conductivity and high surface area; these properties are essential for supercapacitor electrodes. Utilizing fly ash for producing carbon-based supercapacitor electrodes is more cost-effective compared to conventional methods, making it an attractive option for large-scale applications. Research has shown that fly ash-derived carbon materials exhibit good electrochemical properties, including high specific capacitance, excellent charge/discharge rates, and long cycle stability. Moreover, processed fly ash generates silica, alumina, and other metal oxides that can be used as anode materials and cathode materials in batteries. These materials can enhance the capacity and stability of batteries. Fly ash can be used to create doped carbon structures, such as nitrogen-doped carbon, which can improve the conductivity and electrochemical performance of battery electrodes. Certain components of fly ash can be used as additives in electrolytes to enhance the ionic conductivity and overall performance of batteries. Recent studies have focused on creating composites containing fly ash and other materials, such as polymers or metal oxides, to enhance the electrochemical properties and stability of supercapacitors and batteries. Researchers are exploring environmentally friendly synthesis methods to process fly ash into valuable components for energy storage, minimizing the environmental footprint of both fly ash disposal and energy storage device production [82–87].

Pransisco et al. investigated the potential of using recycled fly ash to create supercapacitor electrodes. Fly ash contains metal oxides like iron oxide and aluminum oxide; this material is potentially useful for storing energy. The researchers combined fly ash with 3D graphene, a highly conductive material fabricated using a low-pressure chemical vapor deposition (LPCVD) approach. Fly ash was coated onto the 3D graphene base to create the composite electrode. The team evaluated the characteristics of the electrode using a 3-electrode system and cyclic voltammetry. Their findings suggest that the 3D graphene/fly ash (FA) electrode achieved a maximum specific capacitance of around 0.025 F/cm^2 at the lowest scan rate (5 mV/s). While this capacitance is modest, the study highlights the possibility of utilizing waste fly ash material for supercapacitor applications, potentially promoting resource recovery and more sustainable energy storage solutions [82].

Wang et al. present a novel method to create high-performance supercapacitor electrodes from fly ash. Their approach involved the conversion of problematic crystalline silica in fly ash to cobalt-iron silicate (CoFeSiSx) through high-temperature calcination and a one-step hydrothermal ion exchange process. The fly ash is etched to create a 3D porous structure, enhancing its potential for energy storage. Electrostatic self-assembly and sulfurization further improved the ability of the material to conduct electrons. By combining these strategies, the researchers successfully overcame the limitations of using fly ash directly in supercapacitor applications. The resulting CNFs/FA-CoFeSiSx electrode material exhibits impressive performance with a high specific capacitance of 493.33 F/g^{-1} at a current density of 0.5 A/g^{-1} and a coulombic efficiency of ~ 100% at a high current density of 10 A/g^{-1}. The system retained around 79.50% capacitance after 1800 charge–discharge cycles. Furthermore, the study demonstrated the assembly of a high-performing asymmetric supercapacitor using the CNFs/FA-CoFeSiSx electrode. This achievement highlights the potential for fly ash to be a valuable resource in developing sustainable and cost-effective energy storage solutions [83].

Lie et al. investigated a new method for transforming coal fly ash (FA) waste into a high-performance supercapacitor (SC) electrode material. Their approach utilizes subcritical water extraction (SWE), a pressurized hot water treatment under acidic conditions. This process removed unwanted substances from the fly ash and enhances its electrical conductivity, making it suitable for SC applications. The researchers studied how the acid concentration during SWE affects the final performance of the electrode. The FA electrode pre-treated with 0.5 M acid in SWE (FA-0.5) demonstrated the most promising results. This electrode achieved a high specific capacitance (620 F g^{-1}), good energy density (22 Wh kg^{-1}), and impressive power density (500 W kg^{-1}) at a specific current density. The presence of silicon dioxide and metal oxides in the FA-0.5 sample is believed to contribute to its energy storage capability. Furthermore, the study successfully assembled a full supercapacitor cell using FA-0.5 as the positive electrode (cathode) and activated carbon as the negative electrode (anode). This asymmetric cell delivered a remarkable energy density (99 Wh kg^{-1}) and power density (1600 W kg^{-1}) at a high current density. This research paved the way for a valuable waste-to-resource approach. By employing a novel SWE technique, fly ash can be transformed into a high-performance energy storage material, promoting resource recovery and the development of sustainable energy solutions [84].

Jiang et al. presented a novel and sustainable approach to create high-performance silicon nanorods (SiNRs) for lithium-ion battery (LIB) anodes. They leveraged electrospinning, a cost-effective and scalable technique, to generate initial structures from fly ash. The fly ash-derived structures were then modified by magnesiothermic reaction to transform them into SiNRs. Notably, fly ash is a rich source of silica (around 40%), making this process environmentally friendly and cost-effective compared to using other silicon sources. The resulting SiNRs possessed a unique structure with a porous interior and a thin silicon oxide (SiOx) layer on the surface. This structure helped to accommodate the changes in volume that take place during lithium ion charging and discharging, reducing stress on the SiNRs. When tested as LIB anodes, these SiNRs demonstrate outstanding performance, with a reversible capacity exceeding 1136.8 mAh g^{-1} after 100 cycles at a current density of 0.5 C. This research offers a promising strategy for utilizing waste materials like fly ash to create high-performance and sustainable anode materials for next-generation lithium-ion batteries [85].

Wang et al. described a new approach to improve the performance of aluminum batteries (ALBs). They incorporated fly ash (FA) particles as a functional filler into the composite polymer electrolyte (CPE) used in the battery. The FA particles helped to trap free anions within the electrolyte, preventing them from undergoing decomposition at the interface between the cathode and the electrolyte. This approach significantly enhanced the long-term stability of the battery. FA-enhanced CPEs demonstrated excellent cycling performance, indicating their ability to maintain high capacity over many charge–discharge cycles (Fig. 7). By immobilizing anions within the electrolyte using FA particles, researchers achieved a more stable and higher-performing battery design. This approach paved the way for further advancements in aluminum battery technology [86].

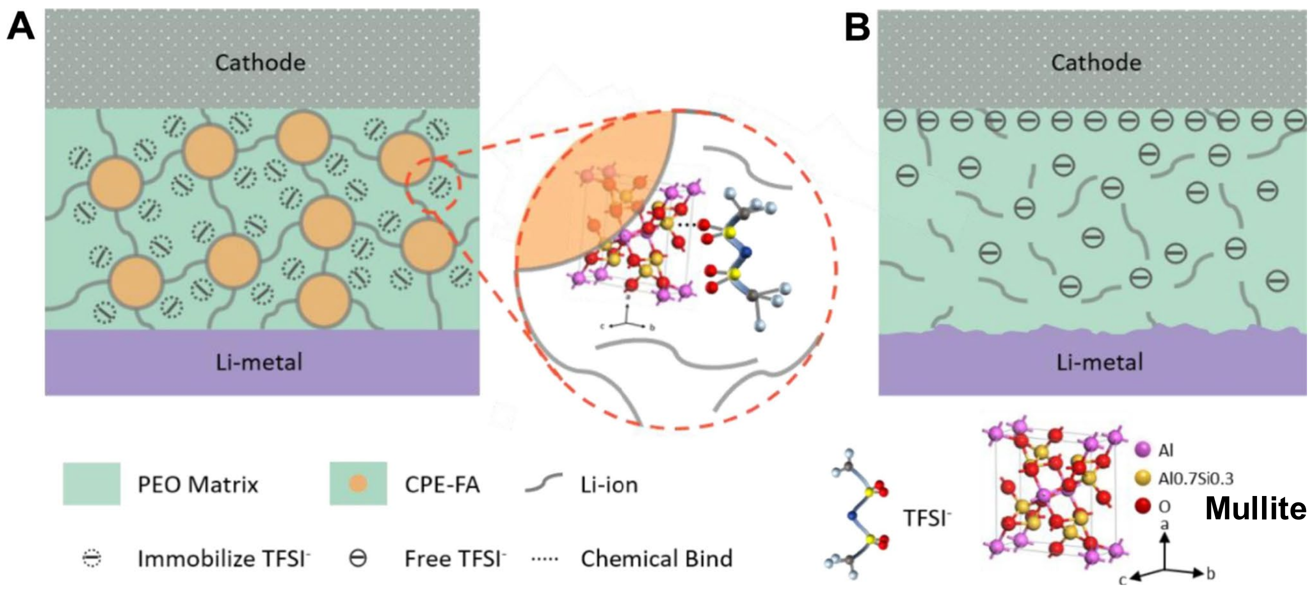

Fig. 7 Schematic showing the ionic diffusion characteristics of the cells with **A** CPE-FA and **B** SPE-PEO during the charge process [86]

Ajorloo et al. investigated the potential of using recycled materials in car parts traditionally made from polypropylene (PP). The researchers investigated the incorporation of both recycled PP and fly ash, a waste product, into the PP composite formulation. While increasing the amount of recycled PP in the composite reduced its flexibility and impact resistance, it also led to better dispersion of filler particles (like fly ash) due to lower viscosity; this approach improved the tensile strength of the composite. However, recycled PP also lowered the crystallinity and melting temperature of the material. Fly ash offered an advantage over traditional filler materials like talc by maintaining higher ductility (flexibility) in the composite. Combining fly ash with talc further enhanced ductility but came at the cost of reduced impact strength compared to talc alone. The study suggested that using a 20/80 to 40/60 ratio of recycled PP to virgin PP offers a good balance for car parts. This approach not only reduced production costs but also promoted sustainable and environmentally friendly manufacturing by utilizing waste materials [87].

Sensors

Utilizing fly ash for electrochemical sensing applications is a promising area of research that takes advantage of the unique properties of this industrial by-product to develop efficient and cost-effective sensors. Fly ash-based sensors can be used to detect heavy metals such as cadmium (Cd), lead (Pb), and mercury (Hg) in water. The high surface area and active sites of fly ash-derived carbon materials enable effective adsorption and detection of these toxic metals. Sensors made from fly ash can detect organic pollutants such as phenols, pesticides, and dyes. These sensors can be employed in environmental monitoring to ensure water and soil safety. Fly ash can be used to develop biosensors for detecting biological molecules such as glucose, cholesterol, and DNA. Modified fly ash materials can be functionalized with enzymes or antibodies to create highly specific and sensitive biosensors. Fly ash-based materials can be used to detect gases like ammonia, hydrogen, and nitrogen oxides. The porous structure and high conductivity of fly ash-derived materials enhance the sensitivity and response time of gas sensors. Researchers have synthesized carbon nanotubes from fly ash, which exhibit excellent electrical conductivity and high surface area; these characteristics are ideal for electrochemical sensing applications. Fly ash can be combined with metal oxides, including zinc oxide (ZnO) and titanium dioxide (TiO_2), to create composite materials with enhanced sensing properties. These composites can improve the selectivity and sensitivity of sensors for specific analytes. Functionalizing fly ash with various chemical groups or nanoparticles can enhance its interaction with target analytes, improving the performance of electrochemical sensors [88–92].

Barros et al. investigated the potential of fly ash (FA) as a modifier for electrodes used in heavy metal detection. They created graphite/polyurethane composite electrodes (GPUE) and incorporated varying amounts of FA. The researchers employed techniques like SEM, EDX, TGA, and DTG to analyze the characteristics of these composite materials. They then evaluated the performance of the electrodes, with and without FA modification, in detecting cadmium (Cd (II)) ions using a voltammetry technique. After optimizing various parameters, they established a reliable detection method using GPUE modified with 5% FA (by weight). The electrode exhibited a linear response for Cd (II) detection within a specific concentration range, with a very low detection limit (LOD) for Cd (II), enabling the identification of even trace amounts. These findings suggest that fly ash can be a valuable material for modifying electrodes, promoting a more sustainable and cost-effective approach to heavy metal detection in environmental and industrial settings [88].

Another study by Ghanjaoui et al. explored the potential of fly ash (FA) waste from power plants to enhance the detection of bisphenol A (BPA) in water. The researchers modified the fly ash (MFA) and characterized it using SEM, XRF, and XRD. They then incorporated the MFA into a carbon paste electrode (CPE), creating a cost-effective electrochemical sensor (MFA/CPE) for BPA detection. The research focused on optimizing sensor performance by fine-tuning the MFA/CPE ratio to ensure the best detection sensitivity and solution conditions. MFA/CPE sensor demonstrated a linear detection range between 2.5 and 125 μM, with a low detection limit of 0.31 μM for BPA, indicating high sensitivity. Common substances like hydroquinone and catechol did not interfere with the ability of the sensor to detect BPA accurately [89].

Kanakaraju et al. combined the strengths of metal-treated titanium dioxide (titania) and the adsorption capabilities of fly ash to create a more powerful photocatalyst for water treatment. Photocatalysts use light to drive chemical reactions, and this study aims to improve water remediation by designing a material with multifaceted properties. Among various options of dopant metals for incorporation into titania, copper (Cu) has emerged as a promising candidate due to its well-documented effectiveness. The advantage of copper stems from the narrow band gap energies of its oxides (CuO 1.4 eV and Cu_2O 2.2 eV), which play a key role in the photocatalytic process. Additionally, copper offers several practical benefits. Unlike some dopants such as silver (Ag), copper is less toxic, readily available, and cost-effective. Incorporating copper into the titania structure modifies its band gap and reduces the recombination of electron–hole pairs generated by light. This approach ultimately enhanced the catalytic activity of the doped titania, making it a more efficient material for water treatment [90].

Teng et al. explored a novel approach for wastewater treatment using a three-dimensional electrochemical system (3DES). Their method involves electrodes fabricated from fly ash (FA) and red mud (RM) particles combined in various ratios (FRPEs). The group investigated how different factors like FRPE ratio and operational parameters such as cell voltage, initial solution pH, and FRPE dosage influenced the degradation of atrazine (ATZ), a common herbicide, in wastewater. The optimal ratio of fly ash to red mud in the electrodes (FRPEs) was identified for maximizing ATZ degradation. Under these optimized conditions (FA:RM = 3:4, FRPE dosage 100 g/L, cell voltage 5 V, initial pH 6.8, and 30-min treatment), the system achieved a remarkable 90.1% degradation rate for ATZ (Fig. 8). Furthermore, the FRPE electrodes demonstrated good stability and reusability. They maintained high activity even after seven recycling cycles, highlighting their potential for long-term wastewater treatment applications. The study also proposes a possible mechanism for ATZ degradation within the 3DES system, suggesting hydroxyl radicals (·OH) as the primary active species responsible for the breakdown process [91].

Huang et al. designed an electrochemical system to study how chloride (Cl^-) behaves in fly ash obtained from municipal solid waste incineration (MSWI) during a process called electrokinetic (EK) treatment. This approach involves applying an electrical current to the fly ash. The researchers investigated how different treatment duration, voltage applied, and silicate content affected the movement and transformation of Cl within the fly ash. For each test, they meticulously analyzed the treated fly ash to understand the Cl distribution. Their findings revealed that the EK treatment caused Cl ions to migrate towards the positive electrode (anode) primarily from the surface layer of the fly ash. Adding silicate material improved the uniformity of Cl distribution throughout the fly ash sample. The formation of a calcium-silicate-hydrate (C-S–H) compound during treatment reduced the movement of calcium ions (Ca^{2+}). This limited competition with Cl ions for movement within the fly ash, ensuring efficient Cl migration. The addition of silicate appears to be a beneficial strategy for promoting Cl removal and achieving a more even distribution within the treated material [92].

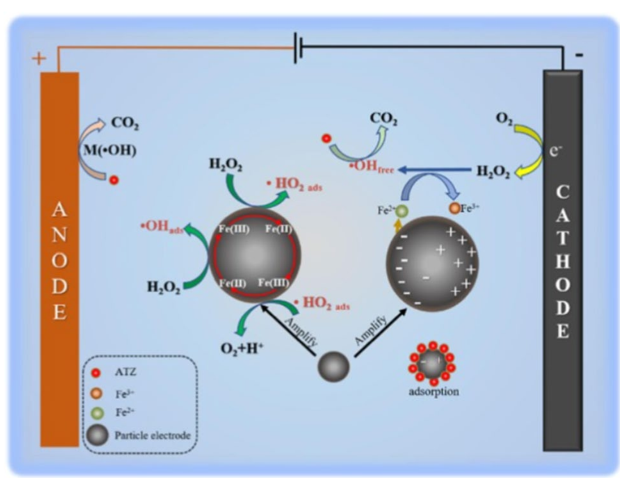

Fig. 8 The possible reaction mechanism associated with 3DES [91]

Table 1 Summary of fly ash-based applications

Applications				Ref
Electrocatalyst	DSSCs	Material	Efficiency %	
		PEDOT: PSS and fly ash composite on FTO-glass	4.23	70
		PEDOT: PSS/TiO_2NPs/fly ash composite	8.49	73
		FA-based zeolites	4.8–6.0	74
		Activated carbon/fly ash/PEDOT: PSS composites	5.81	94
		FA_SiO_2	5.5	95
		Oily FA-based activated carbon	5.45	96
			Peak potentials	
	ORR	Coal fly ash char	0.67 V	76
		Coal char/fly ash	0.42–0.75 V	77
	HER/OER		Overpotential	
		Fe_3O_4-fly ash/graphite/carbon cloth	0.175/0.328 V	20
		FA-TiO_2	0.125 V	72
			Peak current	
	Methanol oxidation	Bio-$CuWO_4$ NCs	3.6 mA cm^{-2}	78
		Pt/Faujasite-C	11 mA cm^{-2}	97
		FAU zeolite type X/PtNPs	0.84–1.07 mA cm^{-2}	98
		Beta–zeolites	2.5 mA cm^{-2}	99
		ZrO_2/sugarcane bagasse (SCB) FA		100
			LOD/adsorption capacities/efficiency	
Sensing/Removal	Heavy metals	GPUE/FA–Cd (II)	6.6×10^{-8} mol L^{-1}	89
		MSWI FA–Cd, Cr, Cu, Pb, Zn	44.87–10.83 mg/g	101
		Fractionated FA-As, Cd, Cr, Cu, Ni, Pb, Zn	30–40 mg/kg	102
		Ca_2SiO_4/FA-Ni (II), Cu (II), Zn (II), Co (II)	235.2–680.93 mg/g	103
		FA / Zeolite NaP1-Zn, Cu, Pb	14.5–192 mg/g	104
		Surfactant modified FA-Cd (II), Hg (II)	11.01–12.14 mg/g	105
		Coal FA-Pb, Cu, Cd, Cr, Zn	4.3 to 5.2 mg/g	106
		$(FeO)_x$NPs–FA–Pb, Cr	40 70%	107
		MicroFA–nanoTiO_2-Cu (II), Cd (II)/surfactants	13.9–86.2 mg/g	108
			Inhibition efficiency/impedance	

Table 1 (continued)

Applications				Ref
Coatings	Anticorrosion/metals	FA-PANI-Fe-F	7.1×10^8 Ω·cm^2	79
		CFZ–FA-steel	86.06%	80
		Polyester amide resin/ZnO-Al_2O_3-FA/MWCNTs	–	82
		Ni–Coal FA on zinc rich coatings	–	109
		(GO)-FA cenospheres–epoxy coatings	–	110
		Mesoporous NaY zeolites–FA	10^6 Ω·cm^2	111
		PPy-Ash-adenosine/epoxy	4.25 Ω	112
		GPTMS FAC–epoxy	5%	113
			Water contact angle	
	Hydrophobic	Chemically modified FA	154.7°	114
		$CaCO_3$NPs–ultrafine FA	> 150°	115
		Cotton textile–FA	152°	116
		FA/polytetrafluoroethylene (PTFE)	147°	117
		Benzoxazine/zeolite A–FA	158.8° ± 0.9°	118
		PDMS/FA	155°	119
		Oleic acid–FA	87°	120
		Trimethoxy(octadecyl)silane (OTMS)–FA	143–153°	121
		Ceramic membrane–FA	151.3°	122
	Cementitious		Tensile strength MPa/% increase	
		GO nanosheets–FA	31–56.4	123
		CNTs–FA	14.2–25.8	124
		FA-micro poly-vinyl-alcohol (PVA) fibers	4.63–5.41 MPa	125
Electrode modification	Supercapacitor		Specific capacitance	
		3D graphene/FA	0.025 F/cm^2	83
		Carbon nanofibers (CNFs)/FA-CoFeSiSx	493.33 F·g^{-1}	84
		N/P/O co-doped hierarchical porous carbon (HPCs)/FA	522 F·g^{-1}	126
		FA/SiO_2 nano matrix–spinel $NiFe_2O_4$	974 F·g^{-1}	127
		CFA–aluminum MOF	306.59 F g^{-1}	128
		FA/NiO_3Si–oxygen vacancies	263.95 mAh g^{-1}	129
	Batteries		Charge capacity	
		FA–Si nanomaterials	1136.68 mAhg^{-1}	85
		Composite polymer electrolyte (CPE)–FA poly (ethylene oxide) (PEO) matrix	-	86
		FA–SiO_2/C composite	586 mAh g^{-1}	130
		Unburnt carbon	325.5 mAh g^{-1}	131
		FA/nanostructured silicon–LIBs	1450.3 mAh g^{-1}	132
		Lithium ferriphospat ($LiFePO_4$), FA, acethylene black (AB)	94.373 mAh g^{-1}	133
		Ni-coated FA microballoons–Pb alloy melt	111.81 mAh g^{-1}	134

Common themes and divergences in studies

A comparison of recent studies involving the usage of fly ash in four major areas covered in this review is summarized in Table 1 [18, 93–132]. In the case of solar cell applications, each study approaches the use of fly ash in DSSCs differently; they collectively demonstrate the potential of fly ash as a sustainable and cost-effective material. In one investigation, fly ash was mixed with PEDOT to form a composite material used for the counter electrode in DSSCs. These cells achieved an efficiency of 7.2%, which was higher than blank PEDOT [93]. The addition of fly ash improved the conductivity and catalytic activity of PEDOT, leading to enhanced photovoltaic performance. Similarly, another group derived carbonaceous materials from processed fly ash, which were then incorporated into PEDOT. These DSSCs reached an efficiency of 7.8%, showing a significant improvement over standard PEDOT electrodes. The derived carbon from fly ash provided better electron transport and catalytic properties, contributing to higher efficiency. Another group performed surface modification of fly ash with acid treatment and metal doping before blending it with PEDOT. This resulting composite achieved an efficiency of 8.1%, the highest among the studies reviewed. Surface alteration enhanced the compatibility and performance of fly ash in the PEDOT matrix, resulting in superior efficiency. In another study, fly ash was combined with PEDOT along with carbon nanotubes to form hybrid nanocomposites. These hybrid nanocomposite-based DSSCs achieved an efficiency of 8.3%. The synergistic effects of fly ash, PEDOT, and nanomaterials significantly boosted the overall performance and stability of the DSSCs. Another study revealed that electrodes based on fly ash-doped PEDOT and other conductive polymers could achieve an efficiency of 7.6%. The use of polymer blends improved the mechanical characteristics and durability of the electrodes, making them suitable for long-term applications.

Fly ash has also been successfully used for the development of anticorrosive coatings. In one study, a mixture of fly ash and epoxy resin was used to create a composite coating for steel substrates. These coatings exhibited excellent adhesion and reduced corrosion rates by 40% compared to bare steel. The incorporation of fly ash improved the barrier properties of the coating, enhancing its anticorrosive performance. Similarly, zinc and fly ash-based hybrid coatings demonstrated a 35% improvement in corrosion resistance compared to traditional zinc coatings. Fly ash particles contributed to better dispersion and adhesion of zinc, leading to enhanced protective properties. Studies reveal that a fly ash-integrated potassium silicate binder can show a 50% reduction in corrosion rates compared to uncoated metal. The addition of fly ash improved the mechanical properties of the coating and increased its resistance to environmental degradation. Another investigation suggests that a fly ash and polyurethane mixture can form a durable coating for steel structures, exhibiting superior abrasion resistance and a 45% decrease in corrosion rates. The fly ash particles enhanced the mechanical strength and durability of the coating, making it suitable for harsh environments. Similarly, a graphene oxide and fly ash nanocomposite-based coating applied to materials like aluminum alloys achieved a 60% improvement in corrosion resistance compared to standard coatings. The synergy between fly ash and graphene oxide resulted in enhanced barrier properties and better protection against corrosion.

Fly ash-based supercapacitors have achieved significant improvements in specific capacitance with different blends. In one approach, porous carbon derived from the chemical activation of fly ash was used to create supercapacitor electrodes. These supercapacitors demonstrated a specific capacitance of 150 F/g at a current density of 1 A/g. The porous structure provided a high surface area, enhancing the electrochemical performance. Similarly, activated carbon produced from the physical activation of fly ash showed a specific capacitance of ~ 160 F/g at 1 A/g. The activation process increased the surface area and porosity, contributing to better electrochemical properties. Fly ash-derived carbon nanofiber electrodes achieved a specific capacitance of 180 F/g at 1 A/g, with good rate capability as well as cyclic stability [109–128, 133–142]. The nanofiber structure provided a large surface area and efficient electron transport pathways, improving overall performance. Another study on the development of fly ash and carbon nanotube (CNT) hybrid electrodes revealed that these electrodes could exhibit a specific capacitance of 220 F/g at 0.5 A/g and maintain 90% of their initial capacitance after 10,000 cycles. The combination of fly ash and CNTs resulted in enhanced electrical conductivity, mechanical strength, and electrochemical performance, with excellent long-term stability. Hybrid materials, particularly those combining fly ash with graphene or CNTs, achieved the best results, suggesting that further research and optimization could lead to highly efficient and sustainable supercapacitor solutions [96–118].

Major findings, technological advancements, and challenges in electrochemical usage

The use of fly ash in electrochemical applications has shown promising results across various fields, including energy storage, environmental remediation, catalysis, and sensing

[10–18, 93–127]. Fly ash-derived carbon materials have been successfully used as anodes in lithium-ion batteries. These materials offer high specific capacity, good cycling stability, as well as excellent rate performance [128–131]. Fly ash can be processed into porous carbon materials, which serve as effective electrode materials in supercapacitors [82–84]. These electrodes demonstrate good charge–discharge rates, high capacitance, and a long cycle life. Fly ash can also be used as an adsorbent in electrochemical processes to remove heavy metals from wastewater, with its high surface area and porous structure enhancing adsorption capacity [11, 59, 99–106]. Electrochemical systems incorporating fly ash have been effective in degrading organic dyes in wastewater, reducing pollution, and improving water quality. Fly ash has been investigated as a catalyst for the electrochemical reduction of CO_2. This process converts CO_2 into useful chemicals or fuels, helping to mitigate greenhouse gas emissions [33, 34, 38, 39, 53, 58, 75, 89, 93, 94, 121, 122]. Fly ash is widely used as a support material for catalysts in fuel cells, providing a cost-effective and stable platform for the dispersion of catalytic particles and enhancing the overall efficiency and durability of the fuel cells. Modified fly ash materials have been developed as electrocatalysts for oxygen reduction reactions and hydrogen evolution reactions, which are crucial for fuel cell performance. Fly ash-based materials have been used to develop electrochemical sensors for detecting environmental pollutants (e.g., heavy metals and organic compounds) [11, 59, 99–106]. These sensors are sensitive, selective, and cost-effective. Fly ash has also been explored in the fabrication of biosensors for medical diagnostics and environmental monitoring, offering a low-cost alternative to traditional materials. Incorporating fly ash in electrochemical systems can lower the energy requirements for various synthesis processes, making them more sustainable and economically viable. Technological advancements in the use of fly ash for electrochemical applications have driven significant progress in several areas. These advancements enhance the performance, efficiency, and sustainability of various electrochemical systems. The key technological advancements include advanced material processing techniques, nanostructuring efforts, electrode fabrication innovations, and catalyst development.

Improved carbonization and activation techniques have enabled the production of high-surface-area carbon materials from fly ash. These materials exhibit excellent electrochemical properties, making them suitable for use in batteries and supercapacitors [82–84]. Microwave-assisted carbonization and activation processes enhance the properties of fly ash-derived carbons by providing more uniform heating and shorter processing times. Techniques to create nanoporous structures from fly ash improve its surface area and porosity, enhancing its performance as an electrode material in energy storage applications and as an adsorbent in environmental remediation. Developing nanocomposites by combining fly ash with other nanomaterials (e.g., graphene and carbon nanotubes) results in materials with superior electrochemical properties. 3D printing technology allows for the fabrication of customized electrode shapes and structures from fly ash-derived materials, optimizing their performance for specific applications. This technology also facilitates the scalable production of complex electrode architectures, enhancing the practical application of fly ash in electrochemical devices. Advanced coating techniques (e.g., atomic layer deposition) improve the stability and conductivity of fly ash-derived electrodes, enhancing their performance in batteries and supercapacitors. Doping fly ash-derived materials with heteroatoms (e.g., nitrogen and sulfur) further enhances their electrochemical properties, such as conductivity and catalytic activity. Developing hybrid catalysts that combine fly ash with metal nanoparticles or metal oxides improves the catalytic performance and durability of fuel cells. Advances in creating non-noble metal catalysts from fly ash reduce the cost of fuel cells while maintaining high catalytic activity and stability. Additionally, developing selective catalysts from fly ash for the electrochemical reduction of CO_2 enables the production of specific chemicals or fuels with higher efficiency and lower energy consumption. Creating regenerative adsorbents from fly ash allows for the repeated use of the materials in water treatment processes, improving sustainability and cost-effectiveness. Combining fly ash-derived carbons with other materials (e.g., conducting polymers or metal oxides) can result in high-energy–density supercapacitors with enhanced performance. Using nanostructured fly ash-derived materials in sensors improves their sensitivity and selectivity for detecting environmental pollutants and biomolecules.

Using fly ash for electrochemical applications presents several challenges despite its potential benefits. These challenges span material properties, processing techniques, and application-specific issues. Key challenges include inconsistent material quality, processing and fabrication difficulties, electrochemical performance, economic and commercial viability, and environmental impact [18, 93–118]. Fly ash composition can vary significantly depending on the coal source and combustion conditions, leading to inconsistencies in the performance of fly ash-derived materials. Ensuring uniform quality and performance requires stringent quality control measures, which can be challenging. Fly ash may contain contaminants such as heavy metals, unburned carbon, and other impurities that affect its suitability and safety for electrochemical applications. Additional processing steps may be needed to remove or mitigate these contaminants, increasing complexity and cost. Advanced processing techniques (e.g., carbonization and activation) can be energy-intensive and costly, potentially offsetting some of the economic benefits of using fly ash. Scaling up laboratory processes to industrial levels while maintaining material quality and performance can be challenging. Handling fly ash poses health and safety risks due to its fine particulate nature, which can become airborne and cause respiratory issues. Managing and disposing of residual waste from processing fly ash require careful planning to minimize environmental impact.

Some fly ash-derived materials may exhibit lower electrical conductivity compared to traditional materials, affecting their performance in batteries and supercapacitors. Achieving desired electrochemical properties (e.g., high capacitance and stability) may require significant modifications or enhancements. Fly ash-derived materials may also degrade or lose effectiveness over time, particularly under harsh operating conditions, making long-term cycling stability a challenge. Advanced processing techniques and material modifications can increase the production cost of fly ash-derived materials. These materials must compete with established, often lower-cost alternatives, which can affect their commercial viability. Ensuring that fly ash-derived materials meet regulatory standards and safety requirements for specific applications can be complex and time-consuming. Gaining acceptance and trust from industry stakeholders and consumers can be challenging, especially when introducing new materials into established markets. The use of fly ash may inadvertently lead to new environmental issues if not properly managed, such as the release of residual contaminants during use. Comprehensive lifecycle assessments are needed to evaluate the overall environmental impact of using fly ash in electrochemical applications, including production, usage, and disposal [18, 89–109].

Conclusions and future prospectives

Fly ash presents a fascinating opportunity for the development of novel and sustainable materials in the field of electrochemistry. Research has demonstrated the potential of fly ash in various electrochemical applications, including battery electrodes, supercapacitors, sensors, and even wastewater treatment. The composition, porosity, and high surface area of fly ash make it a valuable resource for these applications. By transforming fly ash into specific materials or incorporating it into composite structures, researchers have achieved significant advancements. Utilizing fly ash promotes waste resource recovery and reduces the environmental impact that is associated with its disposal. Fly ash is an abundant and relatively inexpensive material, making it an attractive option for developing cost-efficient electrochemical devices.

While the exploration of fly ash for electrochemical applications is promising, there is still room for further development:

1. Continued research is necessary to refine existing applications and optimize the performance of fly ash-based electrochemical devices. This approach might involve improving properties such as conductivity or maximizing capacity and energy density.
2. Exploring new methods for modifying fly ash to enhance its suitability for specific electrochemical needs remains an important area of research. Techniques like doping, activation, and controlled synthesis of desired structures hold promise.
3. Addressing potential environmental concerns related to trace element contamination in fly ash is crucial for responsible and sustainable utilization.
4. Conducting life cycle assessments to evaluate the overall environmental impact of using fly ash in electrochemical devices compared to traditional materials is essential.

Overall, fly ash holds significant potential to revolutionize various areas of electrochemistry. With continued research and development, this readily available waste product can be transformed into valuable resources for creating sustainable and cost-effective electrochemical technologies.

References

1. Vassilev SV, Vassileva CG (2005) Methods for characterization of the composition of fly ashes from coal-fired power stations: a critical overview. Energy Fuels 19(3):1084–1098
2. Fernández-Jiménez A, Palomo A (2005) Composition and microstructure of alkali activated fly ash binder: effect of the activator. Cem Concr Res 35(10):1984–1992
3. Koukouzas N, Hämäläinen J, Papanikolaou D, Tourunen A, Jäntti T (2007) Mineralogical and elemental composition of fly ash from pilot scale fluidised bed combustion of lignite, bituminous coal, wood chips and their blends. Fuel 86(14):2186–2193
4. Zhao Y, Zhang J, Tian C, Li H, Shao X, Zheng C (2010) Mineralogy and chemical composition of high-calcium fly ashes and density fractions from a coal-fired power plant in China. Energy Fuels 24(2):834–843
5. Li C, Li Y, Sun H, Li L (2011) The composition of fly ash glass phase and its dissolution properties applying to geopolymeric materials. J Am Ceram Soc 94(6):1773–1778
6. Okada T, Tomikawa H (2013) Effects of chemical composition of fly ash on efficiency of metal separation in ash-melting of municipal solid waste. Waste Manage 33(3):605–614
7. Cho YK, Jung SH, Choi YC (2019) Effects of chemical composition of fly ash on compressive strength of fly ash cement mortar. Constr Build Mater 204:255–264
8. Korniejenko K, Halyag NP, Mucsi G (2019) Fly ash as a raw material for geopolymerisation-chemical composition and physical properties. IOP Conf Ser: Mater Sci Eng 706(1):012002

9. Kim T, Ley MT, Kang S, Davis JM, Kim S, Amrollahi P (2020) Using particle composition of fly ash to predict concrete strength and electrical resistivity. Cement Concr Compos 107:103493
10. Iwuoha EI, Mavundla SE, Somerset VS, Petrik LF, Klink MJ, Sekota M, Bakers P (2006) Electrochemical and spectroscopic properties of fly ash–polyaniline matrix nanorod composites. Microchim Acta 155:453–458
11. Pedersen AJ, Ottosen LM, Villumsen A (2005) Electrodialytic removal of heavy metals from municipal solid waste incineration fly ash using ammonium citrate as assisting agent. J Hazard Mater 122(1–2):103–109
12. Saraswathy V, Song HW (2006) Electrochemical studies on the corrosion performance of steel embedded in activated fly ash blended concrete. Electrochim Acta 51(22):4601–4611
13. Marin E, Lekka M, Andreatta F, Fedrizzi L, Itskos G, Moutsatsou A, Koukouzas N, Kouloumbi N (2012) Electrochemical study of aluminum-fly ash composites obtained by powder metallurgy. Mater Charact 69:16–30
14. Dong B, Qiu Q, Xiang J, Huang C, Sun H, Xing F, Liu W (2015) Electrochemical impedance interpretation of the carbonation behavior for fly ash–slag–cement materials. Constr Build Mater 93:933–942
15. Cai X, He Z, Shao Y, Sun H (2016) Macro-and micro-characteristics of cement binders containing high volume fly ash subject to electrochemical accelerated leaching. Constr Build Mater 116:25–35
16. Dong B, Wu Y, Teng X, Zhuang Z, Gu Z, Zhang J, Xing F, Hong S (2019) Investigation of the Cl− migration behavior of cement materials blended with fly ash or/and slag via the electrochemical impedance spectroscopy method. Constr Build Mater 211:261–270
17. Heikal M, Ali AI, Ibrahim B, Toghan A (2020) Electrochemical and physico-mechanical characterizations of fly ash-composite cement. Constr Build Mater 243:118309
18. Choi GH, Park J, Bae S, Park JT (2022) Quasi-solid-state SiO2 electrolyte prepared from raw fly ash for enhanced solar energy conversion. Materials 15(10):3576
19. Jia Y, Feng H, Shen D, Zhou Y, Chen T, Wang M, Chen W, Ge Z, Huang L, Zheng S (2018) High-performance microbial fuel cell anodes obtained from sewage sludge mixed with fly ash. J Hazard Mater 354:27–32
20. Cheng T, Chen C, Wen M, Pan F, Zhang X, Ma H, Hou B, Xin X (2024) Low-cost composite electrodes by active Fe3O4 (111) of fly ash magnetic-sphere for efficient electrochemical overall water splitting. Int J Environ Sci Technol, 1–22
21. Su M, Peng H, Li S (2021) A visualized bibliometric analysis of mapping research trends of machine learning in engineering (MLE). Expert Syst Appl 186:115728
22. Tamala JK, Maramag EI, Simeon KA, Ignacio JJ (2022) A bibliometric analysis of sustainable oil and gas production research using VOSviewer. Clean Eng Technol 7:100437
23. Ranjbari M, Esfandabadi ZS, Quatraro F, Vatanparast H, Lam SS, Aghbashlo M, Tabatabaei M (2022) Biomass and organic waste potentials towards implementing circular bioeconomy platforms: a systematic bibliometric analysis. Fuel 318:123585
24. Bajpai R, Choudhary K, Srivastava A, Sangwan KS, Singh M (2020) Environmental impact assessment of fly ash and silica fume based geopolymer concrete. J Clean Prod 254:120147
25. Lieberman RN, Knop Y, Querol X, Moreno N, Muñoz-Quirós C, Mastai Y, Anker Y, Cohen H (2018) Environmental impact and potential use of coal fly ash and sub-economical quarry fine aggregates in concrete. J Hazard Mater 344:1043–1056
26. Gopinathan P, Santosh MS, Dileepkumar VG, Subramani T, Reddy R, Masto RE, Maity S (2022) Geochemical, mineralogical and toxicological characteristics of coal fly ash and its environmental impacts. Chemosphere 307:135710
27 Kozhukhova NI, Lebedev MS, Vasilenko MI, Goncharova EN (2019) Toxic effect of fly ash on biological environment. IOP Conf Ser: Earth Environ Sci 272(2):022065
28. Wang N, Sun X, Zhao Q, Yang Y, Wang P (2020) Leachability and adverse effects of coal fly ash: a review. J Hazard Mater 396:122725
29. Panda RB, Biswal T (2018) Impact of fly ash on soil properties and productivity. Int J Agric, Environ Biotechnol 11(2):275–283
30. Dwivedi A, Jain MK (2014) Fly ash–waste management and overview: a review. Recent Res Sci Technol 6(1):30–35
31. Nayak DK, Abhilash PP, Singh R, Kumar R, Kumar V (2022) Fly ash for sustainable construction: a review of fly ash concrete and its beneficial use case studies. Clean Mater 6:100143
32 Ghazali N, Muthusamy K, Wan Ahmad S (2019) Utilization of fly ash in construction. IOP Conf Ser: Mater Sci Eng 601(1):012023
33. Vargas J, Halog A (2015) Effective carbon emission reductions from using upgraded fly ash in the cement industry. J Clean Prod 103:948–959
34. Hou H, Su L, Guo D, Xu H (2023) Resource utilization of solid waste for the collaborative reduction of pollution and carbon emissions: case study of fly ash. J Clean Prod 383:135449
35. Renjith R, Robert D, Setunge S, Costa S, Mohajerani A (2021) Optimization of fly ash-based soil stabilization using secondary admixtures for sustainable road construction. J Clean Prod 294:126264
36. Mishra R, Singh SK, Gupta H, Srivastava N, Meghnani D, Tiwari RK, Patel A, Tiwari A, Tiwari VK, Singh RK (2021) Surface modification of nano Na [Ni0. 60Mn0. 35Co0. 05] O2 cathode material by dextran functionalized RGO via hydrothermal treatment for high performance sodium batteries. Appl Surf Sci 535:147695
37. Chaurasia SK, Singh RK, Chandra S (2013) Effect of ionic liquid on the crystallization kinetics behaviour of polymer poly (ethylene oxide). CrystEngComm 15(30):6022–6034
38. Ashfaq M, Moghal AAB (2022) Cost and carbon footprint analysis of flyash utilization in earthworks. Int J Geosynth Ground Eng 8(2):21
39. Tosti L, van Zomeren A, Pels JR, Comans RN (2018) Technical and environmental performance of lower carbon footprint cement mortars containing biomass fly ash as a secondary cementitious material. Resour Conserv Recycl 134:25–33
40. Bentz DP, Hansen AS, Guynn JM (2011) Optimization of cement and fly ash particle sizes to produce sustainable concretes. Cement Concr Compos 33(8):824–831
41. Arvaniti EC, Juenger MC, Bernal SA, Duchesne J, Courard L, Leroy S, Provis JL, Klemm A, De Belie N (2015) Determination of particle size, surface area, and shape of supplementary cementitious materials by different techniques. Mater Struct 48:3687–3701
42. Chen R, Li Y, Xiang R, Li S (2016) Effect of particle size of fly ash on the properties of lightweight insulation materials. Constr Build Mater 123:120–126
43. Moon GD, Oh S, Choi YC (2016) Effects of the physicochemical properties of fly ash on the compressive strength of high-volume fly ash mortar. Constr Build Mater 124:1072–1080
44. Wang T, Ishida T, Gu R (2018) A comparison of the specific surface area of fly ash measured by image analysis with conventional methods. Constr Build Mater 190:1163–1172
45. Assi LN, Deaver EE, Ziehl P (2018) Effect of source and particle size distribution on the mechanical and microstructural properties of fly ash-based geopolymer concrete. Constr Build Mater 167:372–380
46. Cui Y, Wang L, Liu J, Liu R, Pang B (2022) Impact of particle size of fly ash on the early compressive strength of concrete:

experimental investigation and modelling. Constr Build Mater 323:126444
47. Feng S, Zhang X, Xu L, Tao W, Duan G (2024) Correlation analysis of various characteristics of fly ash based on particle separation. Case Stud Construct Mater 20:e02785
48. Van Jaarsveld JGS, Van Deventer JS, Lukey GC (2002) The effect of composition and temperature on the properties of fly ash-and kaolinite-based geopolymers. Chem Eng J 89(1–3):63–73
49. Moreno N, Querol X, Andrés JM, Stanton K, Towler M, Nugteren H, Janssen-Jurkovicová M, Jones R (2005) Physico-chemical characteristics of European pulverized coal combustion fly ashes. Fuel 84(11):1351–1363
50. Raclavska H, Raclavsky K, Matysek D (2009) Colour measurement as a proxy method for estimation of changes in phase and chemical composition of fly ash formed by combustion of coal. Fuel 88(11):2247–2254
51. Venkatanarayanan HK, Rangaraju PR (2013) Decoupling the effects of chemical composition and fineness of fly ash in mitigating alkali-silica reaction. Cement Concr Compos 43:54–68
52. Lanzerstorfer C (2015) Chemical composition and physical properties of filter fly ashes from eight grate-fired biomass combustion plants. J Environ Sci 30:191–197
53. Maroto-Valer MM, Zhang Y, Granite EJ, Tang Z, Pennline HW (2005) Effect of porous structure and surface functionality on the mercury capacity of a fly ash carbon and its activated sample. Fuel 84(1):105–108
54. Sinsiri T, Chindaprasirt P, Jaturapitakkul C (2010) Influence of fly ash fineness and shape on the porosity and permeability of blended cement pastes. Int J Miner Metall Mater 17(6):683–690
55. Mishra SB, Langwenya SP, Mamba BB, Balakrishnan M (2010) Study on surface morphology and physicochemical properties of raw and activated South African coal and coal fly ash. Phys Chem Earth, Parts A/B/C 35(13–14):811–814
56. Xu F, Gu G, Zhang W, Wang H, Huang X, Zhu J (2018) Pore structure analysis and properties evaluations of fly ash-based geopolymer foams by chemical foaming method. Ceram Int 44(16):19989–19997
57. Wulandari KD, Ekaputri JJ, Kurniawan SB, Primaningtyas WE, Abdullah SRS, Ismail NI, Imron MF (2021) Effect of microbes addition on the properties and surface morphology of fly ash-based geopolymer paste. J Build Eng 33:101596
58. More AP, Mhaske ST (2016) Anticorrosive coating of polyesteramide resin by functionalized ZnO-Al2O3-Fly ash composite and functionalized multiwalled carbon nanotubes. Prog Org Coat 99:240–250
59. Dash S, Chaudhuri H, Gupta R, Nair UG, Sarkar A (2017) Fabrication and application of low-cost thiol functionalized coal fly ash for selective adsorption of heavy toxic metal ions from water. Ind Eng Chem Res 56(6):1461–1470
60. Astuti W, Chafidz A, Al-Fatesh AS, Fakeeha AH (2021) Removal of lead (Pb (II)) and zinc (Zn (II)) from aqueous solution using coal fly ash (CFA) as a dual-sites adsorbent. Chin J Chem Eng 34:289–298
61. Chougan M, Ghaffar SH, Sikora P, Mijowska E, Kukułka W, Stephan D (2022) Boosting Portland cement-free composite performance via alkali-activation and reinforcement with pre-treated functionalised wheat straw. Ind Crops Prod 178:114648
62. Angaru GKR, Lingamdinne LP, Koduru JR, Chang YY (2022) N-cetyltrimethylammonium bromide-modified zeolite Na-A from waste fly ash for hexavalent chromium removal from industrial effluent. J Compos Sci 6(9):256
63. Jaisankar S, Vijayasharathi N, Sivakumar M, Loganathan GB, Manikandan R, Sakthi S (2023) Prediction of tensile properties of MWCNT/Hemp fibre/fly ash reinforced epoxy polymer composites using various mathematical models. Mater Today: Proc
64. Zhao S, Duan Y, Lu J, Liu S, Pudasainee D, Gupta R, Liu M, Lu J (2018) Enrichment characteristics, thermal stability and volatility of hazardous trace elements in fly ash from a coal-fired power plant. Fuel 225:490–498
65. Kanti P, Sharma KV, Ramachandra CG, Panitapu B (2020) Stability and thermophysical properties of fly ash nanofluid for heat transfer applications. Heat Transfer 49(8):4722–4737
66. Qiu F, Song S, Li D, Liu Y, Wang Y, Dong L (2020) Experimental investigation on improvement of latent heat and thermal conductivity of shape-stable phase-change materials using modified fly ash. J Clean Prod 246:118952
67. Zhang J, Wen X, Cheng F (2021) Preparation, thermal stability and mechanical properties of inorganic continuous fibers produced from fly ash and magnesium slag. Waste Manage 120:156–163
68. Zhang DW, Sun XM, Zhao KF, Xu ZY, Li H (2022) An application of alkali-activated fly-ash materials with low-compressive strength: thermal stability at elevated temperatures. J Build Eng 61:105256
69. Javed U, Shaikh FUA, Sarker PK (2024) Thermal stability and strength degradation of lithium slag geopolymer containing fly ash and silica fume. Constr Build Mater 425:135976
70. Kanjana N, Maiaugree W, Laokul P, Chaiya I, Lunnoo T, Wongjom P, Infahsaeng Y, Thongdang B, Amornkitbamrung V (2023) Fly ash boosted electrocatalytic properties of PEDOT: PSS counter electrodes for the triiodide reduction in dye-sensitized solar cells. Sci Rep 13(1):6012
71. Thirumalai K, Balachandran S, Swaminathan M (2016) Superior photocatalytic, electrocatalytic, and self-cleaning applications of Fly ash supported ZnO nanorods. Mater Chem Phys 183:191–200
72. Altalhi T, Mezni A, Ibrahim MM, Refat MS, Gobouri AA, Safklou AM, Mousli AM, Attia MS, Boruah PK, Das MR, Ryl J (2022) Cathodic activation of titania-fly ash cenospheres for efficient electrochemical hydrogen production: a proposed solution to treat fly ash waste. Catalysts 12(5):466
73. Maiaugree W, Pimanpang S, Towannang M, Saekow S, Jarernboon W, Amornkitbamrung V (2012) Optimization of TiO2 nanoparticle mixed PEDOT–PSS counter electrodes for high efficiency dye sensitized solar cell. J Non-Cryst Solids 358(17):2489–2495
74. Lim JM, Park J, Park JT, Bae S (2019) Preparation of quasi-solid-state electrolytes using a coal fly ash derived zeolite-X and-A for dye-sensitized solar cells. J Ind Eng Chem 71:378–386
75. Alluqmani SM, Loulou M, Ouerfelli J, Alshahrie A, Salah N (2021) Annealing effect on structural and optical properties of nanostructured carbon of oil fly ash modified titania thin films. Result Phys 25:104335
76. Nunes MS, Pereira C, Guedes A, Santos AC, Valentim B, Freire C (2022) Assessment of coal fly ash char as a substituting material of graphite with electrocatalytic activity for the oxygen reduction reaction. Sustain Chem Pharm 27:100705
77. Fernandes DM, Abdelkader-Fernández VK, Badenhorst C, Bialecka B, Guedes A, Predeanu G, Santos AC, Valentim B, Wagner N, Freire C (2021) Coal chars recovered from fly ash as promising electrocatalysts for oxygen reduction reaction. Int J Hydrogen Energy 46(70):34679–34688
78. Thiruppathi M, Leeladevi K, Ramalingan C, Chen KC, Nagarajan ER (2020) Construction of novel biochar supported copper tungstate nanocomposites: a fruitful divergent catalyst for photocatalysis and electrocatalysis. Mater Sci Semicond Process 106:104766
79. Wang Z, Wang C, Fan W, Liu S, Li K, Luo H, Liu S, Wang H (2022) A novel fly ash bifunctional filler for epoxy coating with

long-term anti-corrosion performance under harsh conditions. Chem Eng J 430:133164

80. Rooby DR, Kumar TN, Harilal M, Sofia S, George RP, Philip J (2021) Enhanced corrosion protection of reinforcement steel with nanomaterial incorporated fly ash based cementitious coating. Constr Build Mater 275:122130
81 Chavana N, Bhajantri FV, Jambagi SC (2022) Improvement in slurry erosion and corrosion resistance of plasma-sprayed fly ash coatings for marine applications. ACS Omega 7(36):32369–32382
82. Pransisco P, Balbir Singh MS, Shuaib M, Shukur MF, Joseph E (2020) 3D graphene/fly ash waste material for hybrid supercapacitor electrode: specific capacitance analysis. Materialwiss Werkst 51(6):713–718
83. Wang H, Wang M, Zhang J, Wang N, Wang J, Yang J (2022) Preparation of fly ash-based cobalt-iron silicate as supercapacitor electrode material. Chem Eng J 434:134661
84. Lie J, Shuwanto H, Abdullah H, Ismadji S, Warmadewanthi IDAA, Soetaredjo FE (2023) Fly ash electrodes fabricated by an acid-assisted subcritical water extraction method for supercapacitor applications. New J Chem 47(8):3802–3809
85. Jiang Y, Zhang Y, Yan X, Tian M, Xiao W, Tang H (2017) A sustainable route from fly ash to silicon nanorods for high performance lithium-ion batteries. Chem Eng J 330:1052–1059
86. Wang X, Fu C, Feng Z, Huo H, Yin X, Gao G, Yin G, Ci L, Tong Y, Jiang Z, Wang J (2022) Flyash/polymer composite electrolyte with internal binding interaction enables highly stable extrinsic-interfaces of all-solid-state lithium batteries. Chem Eng J 428:131041
87. Ajorloo M, Ghodrat M, Kang WH (2021) Incorporation of recycled polypropylene and fly ash in polypropylene-based composites for automotive applications. J Polym Environ 29:1298–1309
88. De Barros CR, Cervini P, Buoro RM, van der Merwe EM, Cavalheiro ÉT (2024) Coal fly ash modified graphite-polyurethane composite electrodes for the electrochemical determination of cadmium (II) in batteries and water. Anal Lett 57(8):1282–1301
89. Ghanjaoui ME, Esserrar S, Salmi M, Talhajt SA, Salhi A, El Krati M, El Ghachtouli S, Tahiri S (2024) Rapid and inexpensive method for bisphenol a detection in water samples based on alkaline activated fly ash modified carbon paste electrode. J Appl Electrochem 54(9):1–14
90. Kanakaraju D, Bin Ya MH, Lim YC, Pace A (2020) Combined adsorption/photocatalytic dye removal by copper-titania-fly ash composite. Surf Inter 19:100534
91. Teng X, Li J, Wang J, Liu J, Ge X, Gu T (2021) Effective degradation of atrazine in wastewater by three-dimensional electrochemical system using fly ash-red mud particle electrode: mechanism and pathway. Sep Purif Technol 267:118661
92. Huang T, Zhou L, Yao J, Zhang SW, Li H (2023) Participation influence of silicate on the temporal and spatial distribution of chloride electromigration in the electrokinetics of municipal solid waste incineration fly ashes. J Environ Chem Eng 11(5):110694
93. Kanjana N, Maiaugree W, Wechprasit T, Kaewprajak A, Kumnorkaew P, Wongjom P, Infahsaeng Y (2024) Preparation of a hierarchical porous activated carbon derived from cantaloupe peel/fly ash/PEDOT: PSS composites as Pt-free counter electrodes of dye-sensitized solar cells. Heliyon 10(9):e29957
94. Mehmood U, Aslam MZ, Shawabkeh RA, Hussein IA, Ahmad W, Rana AG (2016) Improvement in photovoltaic performance of dye sensitized solar cell using activated carbon-TiO2 composites-based photoanode. IEEE J Photovolt 6(5):1191–1195
95. Ruiz-Camacho B, Medina-Ramírez A, Aguilera MV, Minchaca-Mojica JI (2019) Pt supported on mesoporous material for methanol and ethanol oxidation in alkaline medium. Int J Hydrogen Energy 44(24):12365–12373
96. Ramírez AM, Aguilera MV, López-Badillo CM, Ruiz-Camacho B (2017) Synthesis of FAU zeolite-C composite as catalyst support for methanol electro-oxidation. Int J Hydrogen Energy 42(51):30291–30300
97. Assawasangrat P, Neramittagapong S, Pranee W, Praserthdam P (2016) Methanol conversion to dimethyl ether over beta zeolites derived from bagasse fly ash. Energ Sourc, Part A: Recov, Utilization, Environ Effect 38(20):3081–3088
98. Abd El-Aal M, Goda MN, Abd El-Wahab MM, El-Gamal NO, Said AEAA (2024) Zirconia–sugarcane bagasse fly ash as a novel solid acid nanocatalyst for selective dehydration of methanol to dimethyl ether. J Chin Chem Soc 71(3):333–344
99. Yao S, Zhang L, Zhu Y, Wu J, Lu Z, Lu J (2020) Evaluation of heavy metal element detection in municipal solid waste incineration fly ash based on LIBS sensor. Waste Manage 102:492–498
100. Dahl O, Nurmesniemi H, Pöykiö R, Watkins G (2010) Heavy metal concentrations in bottom ash and fly ash fractions from a large-sized (246 MW) fluidized bed boiler with respect to their Finnish forest fertilizer limit values. Fuel Process Technol 91(11):1634–1639
101. Ma J, Qin G, Zhang Y, Sun J, Wang S, Jiang L (2018) Heavy metal removal from aqueous solutions by calcium silicate powder from waste coal fly-ash. J Clean Prod 182:776–782
102. Ankrah AF, Tokay B, Snape CE (2022) Heavy metal removal from aqueous solutions using fly-ash derived zeolite NaP1. Int J Environ Res 16(2):17
103. Nguyen TC, Tran TDM, Dao VB, Vu QT, Nguyen TD, Thai H (2020) Using modified fly ash for removal of heavy metal ions from aqueous solution. J Chem 2020(1):8428473
104. Nguyen TC, Loganathan P, Nguyen TV, Kandasamy J, Naidu R, Vigneswaran S (2018) Adsorptive removal of five heavy metals from water using blast furnace slag and fly ash. Environ Sci Pollut Res 25:20430–20438
105. Yadav VK, Amari A, Gacem A, Elboughdiri N, Eltayeb LB, Fulekar MH (2023) Treatment of fly-ash-contaminated wastewater loaded with heavy metals by using fly-ash-synthesized iron oxide nanoparticles. Water 15(5):908
106. Visa M, Duta A (2013) TiO2/fly ash novel substrate for simultaneous removal of heavy metals and surfactants. Chem Eng J 223:860–868
107. Cheng L, Luo Y, Ma S, Guo W, Wang X (2019) Corrosion resistance of inorganic zinc-rich coating reinforced by Ni-coated coal fly ash. J Alloy Compd 786:791–797
108. Li J, Chen P, Wang Y (2021) Tribological and corrosion performance of epoxy resin composite coatings reinforced with graphene oxide and fly ash cenospheres. J Appl Polym Sci 138(11):50042
109. Padhy RR, Shaw R, Tiwari S, Tiwari SK (2015) Ultrafine nanocrystalline mesoporous NaY zeolites from fly ash and their suitability for eco-friendly corrosion protection. J Porous Mater 22:1483–1494
110. Kharat BM, Vyavahare SA, Shirapure Y, Kerosenewala J, Desai P, More AP (2023) Synthesis and characterization of polypyrrole-fly-ash-adenosine composite reinforced epoxy coating for anticorrosive applications. J Appl Polym Sci 140(46):e54685
111. Kogje M, Mestry S, Mohanty JD, Mhaske ST (2024) Modification of fly ash cenospheres by 3-glycidyloxypropyl trimethoxysilane (GPTMS) for anticorrosive coating applications. Iran Polym J 33:1–15
112. Jiang X, Shi J, Chen S, Hou Y, Meng X, Wu G, Xu E (2023) High-valued utilization of fly ash for preparing mechanically robust and multi-scale superhydrophobic coatings. Prog Org Coat 176:107400
113. Song H, Tang M, Lei X, Di Z, Cheng F (2021) Preparation of environment-friendly ultrafine fly ash based superhydrophobic demoulding coating. Appl Surf Sci 566:150688

114. Wang J, Han F, Zhang S (2016) Durably superhydrophobic textile based on fly ash coating for oil/water separation and selective oil removal from water. Sep Purif Technol 164:138–145
115. Chindaprasirt P, Rattanasak U (2020) Fabrication of self-cleaning fly ash/polytetrafluoroethylene material for cement mortar spray-coating. J Clean Prod 264:121748
116. Wang M, Wang W, Li S, Liu H, Fan X, Wang Z (2022) A fly ash-derived polybenzoxazine/zeolite A bilayer coating with excellent superhydrophobicity and corrosion resistance. Prog Org Coat 171:107043
117. Kang X, Li Y, Ma X, Sun H (2022) Fabrication and characterization of high performance superhydrophobic organosilane-coated fly ash composites with novel micro–nano-hierarchy roughness. J Mater Sci 57(29):13914–13927
118. Liu P, Feng C, Wang F, Gao Y, Yang J, Zhang W, Yang L (2018) Hydrophobic and water-resisting behavior of Portland cement incorporated by oleic acid modified fly ash. Mater Struct 51:1–9
119. Khan MZ, Baheti V, Militky J, Ali A, Vikova M (2018) Superhydrophobicity, UV protection and oil/water separation properties of fly ash/trimethoxy (octadecyl) silane coated cotton fabrics. Carbohyd Polym 202:571–580
120. Fu H, Li Z, Zhang Y, Zhang H, Chen H (2022) Preparation, characterization and properties study of a superhydrophobic ceramic membrane based on fly ash. Ceram Int 48(8):11573–11587
121. Cheng Z, Liu Y, Wu J, Guo X, Chen W, Gao Y (2023) Graphene oxide-coated fly ash for high performance and low-carbon cementitious composites. J Market Res 25:6710–6724
122. Chen W, Liu Y, Wu J, Lu S, Han G, Wei X, Gao Y (2023) Enhancing cementitious grouting performance through carbon nanotube-coated fly ash incorporation. Constr Build Mater 409:133907
123. Şahmaran M, Özbay E, Yücel HE, Lachemi M, Li VC (2012) Frost resistance and microstructure of Engineered Cementitious Composites: influence of fly ash and micro poly-vinyl-alcohol fiber. Cement Concr Compos 34(2):156–165
124. Zheng G, Huang Z, Liu Z (2021) Cooperative utilization of beet pulp and industrial waste fly ash to produce N/P/O self-co-doped hierarchically porous carbons for high-performance supercapacitors. J Power Sources 482:228935
125. Christopher IFF, Karuppiah A, Thanapalan VG, Selestin AV, Suyambu T (2023) SiO2 nanomatrix engendered from coal fly ash encrusted with NiFe2O4 nanocomposites for high-performance supercapacitor. Braz J Phys 53(6):149
126. Rambau KM, Tarimo DJ, Fasakin O, Musyoka NM, Manyala N (2022) Asymmetric supercapacitor based on novel coal fly ash derived metal–organic frameworks as positive electrode and its derived carbon as negative electrode. J Appl Electrochem 52(5):821–834
127. Wang M, Wang H, Wang N, Liu X, Wang S, Yang J (2022) The introduction of oxygen vacancy defects in Al-doped transition metal silicates derived from fly ash for high-performance aqueous potassium ion capacitor. Electrochim Acta 434:141310
128 Jumari A, Yudha CS, Widiyandari H, Lestari AP, Rosada RA, Santosa SP, Purwanto A (2020) SiO2/C composite as a high capacity anode material of LiNi0. 8Co0. 15Al0. 05O2 battery derived from coal combustion fly ash. Appl Sci 10(23):8428
129. Yeh TS, Wu YS, Lee YH (2011) Graphitization of unburned carbon from oil-fired fly ash applied for anode materials of high power lithium ion batteries. Mater Chem Phys 130(1–2):309–315
130. Xing A, Zhang J, Wang R, Wang J, Liu X (2019) Fly ashes as a sustainable source for nanostructured Si anodes in lithium-ion batteries. SN Appl Sci 1(2):181
131. Febiolita B, Khoirunnissak D, Purwanto A (2016) Investigation on the fly ash thermal treatment on the performance of lithium ferriphosphate (LiFePO4) battery. In AIP Conference Proceedings 1710(1). AIP Publishing, pp 030051
132. Daoud A, Shenouda AY, Abou El-Khair MT, Fairouz F, Mohamed E, Aziz MA, Yanamandra K, Gupta N (2023) Electrochemical performance of novel Pb alloys reinforced with Ni-coated fly ash microballoon composite foams in Lead Acid Battery. Mater Chem Phys 294:126987
133. Joshi P, Shukla S, Gupta S, Riley PR, Narayan J, Narayan R (2022) Excimer laser patterned holey graphene oxide films for nonenzymatic electrochemical sensing. ACS Appl Mater Interf 14(32):37149–37160
134. Shukla S, Joshi P, Riley P, Narayan RJ (2022) Square wave voltammetric approach to leptin immunosensing and optimization of driving parameters with chemometrics. Biosens Bioelectron 216:114592
135. Kadian S, Shukla S, Narayan RJ (2023) Probes for noninvasive biological visualization and biosensing of cancer cells. Appl Phys Rev 10(4):041304
136. Shukla S, Jakowski J, Kadian S, Narayan RJ (2023) Computational approaches to delivery of anticancer drugs with multidimensional nanomaterials. Comput Struct Biotechnol J 21:4149–4158
137. Shukla S, Khanna S, Sahoo S, Joshi N, Narayan R (2024) Nanomaterial-coated carbon-fiber-based multicontact array sensors for in vitro monitoring of serotonin levels. ACS Appl Bio Mater 7(1):472–484
138. Tabish TA, Zhu Y, Shukla S, Kadian S, Sangha GS, Lygate CA, Narayan RJ (2023) Graphene nanocomposites for real-time electrochemical sensing of nitric oxide in biological systems. Appl Phys Rev 10(4):041310
139. Shukla S, Joshi NN, Kadian S, Narayan RJ (2024) Development of drug-loaded PCL@ MOF film enclosed in a photo polymeric container for sustained release. ACS Appl Bio Mater 7(8):5382–5396
140. Shukla S, Singh S, Mitra MD (2020) Photosensitizer modulated turn–off fluorescence system and molecular logic functions for selective detection of arsenic (III). ChemistrySelect 5(43):13609–13618
141. Pandey PC, Shukla S (2018) Solvent dependent fabrication of bifunctional nanoparticles and nanostructured thin films by self assembly of organosilanes. J Sol-Gel Sci Technol 86:650–663
142. Kadian S, Kumari P, Sahoo SS, Shukla S, Narayan RJ (2024) Machine learning enabled microneedle-based colorimetric pH sensing patch for wound health monitoring and meat spoilage detection. Microchem J 200:110350