1 Introduction to Various Fly Ash (Coal & Bio-Coal) Generated from Industrial Operations

Siddhartha Pandey, Tuhin Sengupta, Nitin Kumar Singh, Gaurav Kabra, Navneet Kumar and Jinsub Park

1.1 INTRODUCTION

Fly ash, a byproduct obtained by the combustion of coal and bio-coal, is an industrial waste material that has gained significant importance in various applications due to its unique properties. Fly ash is primarily composed of fine particles that are carried out of the boiler with the flue gases during the combustion process. This material is captured by pollution control equipment, such as electrostatic precipitators or bag filters before the flue gases are released into the atmosphere. The importance of fly ash lies not only in its abundance but also in its potential as a resource for various industrial processes, particularly in the construction sector (Alrefaei et al., 2021). The composition and properties of fly ash can vary significantly depending on the type of coal or bio-coal used, the combustion conditions, and the efficiency of the pollution control equipment. Typically, fly ash from coal combustion contains silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3), while fly ash from bio-coal combustion may also contain a higher proportion of unburned carbon and other organic compounds (Wang et al., 2020). Coal-fired power plants have traditionally been the largest source of fly ash, producing millions of tons of this material annually. The combustion of coal generates two main types of ash: bottom ash, which is collected at the bottom of the furnace, and fly ash, which is lighter and carried with the flue gases (Yao et al., 2015). The increasing use of bio-coal, a renewable and more sustainable alternative to traditional coal, has led to the production of bio-coal fly ash (BFA), which has similar characteristics to coal fly ash but may differ in terms of chemical composition and potential applications (Wang et al., 2020). The production of fly ash is influenced by several factors, including the type of coal or bio-coal used, the combustion temperature, and the design of the boiler and pollution control equipment (Chindaprasirt and Rattanasak, 2010). Pulverized coal combustion (PCC), which is the most common method used in power plants, produces fly ash with a relatively

DOI: 10.1201/9781003498124-1

high proportion of fine particles. In contrast, fluidized bed combustion, often used for burning low-grade coal or bio-coal, generates fly ash with a higher content of unburned carbon and larger particle sizes (Wang et al., 2020).

Fly ash has become a valuable resource in various industrial processes due to its pozzolanic properties, which allow it to react with lime in the presence of water to form compounds with cementitious properties. This makes fly ash an ideal material for use in the construction industry, particularly in the production of concrete and cement (Fernández-Jiménez and Palomo, 2003). The use of fly ash in concrete not only improves the strength and durability of the material but also reduces the need for Portland cement, leading to significant cost savings and a reduction in carbon emissions (Provis and Bernal, 2015). The use of fly ash in cement and concrete production is one of the most well-established applications, with several standards and guidelines in place to ensure the quality and performance of fly ash-based products. Fly ash can be used as a partial replacement for Portland cement, with replacement levels typically ranging from 15% to 30%, depending on the specific requirements of the project. The inclusion of fly ash in concrete mixtures can improve workability, reduce water demand, and enhance the long-term strength and durability of the concrete (Yao et al., 2015). In addition to its use in cement and concrete production, fly ash is also used in other industrial applications, such as road construction, soil stabilization, and the manufacture of building materials (Provis and Bernal, 2014). For example, fly ash can be used as a filler material in asphalt mixtures, improving the strength and stability of the pavement. It can also be used in the production of bricks, tiles, and other building products, offering a sustainable alternative to traditional materials (Chindaprasirt and Rattanasak, 2010). The chemical composition of fly ash, particularly its high silica and alumina content, makes it suitable for use in the production of geopolymers, a class of materials that are gaining popularity as a sustainable alternative to conventional cement. Geopolymers are formed by the reaction of aluminosilicate materials, such as fly ash, with alkaline activators, resulting in a hardened material with excellent mechanical and chemical properties. The use of fly ash in geopolymer production not only reduces the demand for natural resources but also helps mitigate the environmental impact of fly ash disposal (Provis and Bernal, 2015).

1.2 ENVIRONMENTAL MANAGEMENT

The management of fly ash has become a critical issue due to the large volumes of material generated and the potential environmental risks associated with its disposal. Fly ash contains trace amounts of heavy metals, such as arsenic, lead, and mercury, which can leach into the soil and groundwater if not properly managed. The improper disposal of fly ash can also lead to air pollution, as fine particles can become airborne and contribute to respiratory problems in nearby communities (Wang et al., 2020). To address these environmental concerns, several regulatory frameworks and guidelines have been established to govern the handling, storage, and disposal of fly ash. In many countries, fly ash is classified as a non-hazardous waste, allowing it to be reused in various applications, provided it meets certain quality standards. However, the classification of fly ash can vary depending on its chemical composition and the presence of hazardous substances (Chindaprasirt and Rattanasak, 2010). The reuse of fly ash in industrial applications offers a sustainable solution to the challenges of fly ash management. By incorporating fly ash into construction materials, road bases, and other products, the need for landfill disposal is reduced, and the environmental impact of fly ash is minimized (Wang et al., 2020). Moreover, the use of fly ash in these applications can lead to significant cost savings and contribute to the conservation of natural elements. In recent years, there has been a growing interest in the development of advanced technologies for the treatment and utilization of fly ash. These technologies aim to enhance the quality of fly ash, making it suitable for use in high-value applications, such as the production of advanced materials and the extraction of valuable minerals. For example, the beneficiation of fly ash, which involves the removal of unburned carbon and other impurities, can improve its performance in cement and concrete applications. Additionally, research on the use of fly ash in carbon capture and storage (CCS) technologies is underway, where it can be used to sequester carbon dioxide and reduce greenhouse gas emissions (Yao et al., 2015).

1.3 SOURCES OF FLY ASH

1.3.1 Coal Combustion

Fly ash is a byproduct of the combustion process in coal-based thermal power plants or industrial boilers. As coal is burned to generate heat, non-combustible mineral impurities in the coal, such as silica, alumina, and iron oxides, are left behind as ash. The combustion process generates two types of ash: bottom ash, which is too heavy to be carried by the flue gases and falls to the bottom of the furnace, and fly ash, which is carried by the flue gases and captured by electrostatic precipitators or bag filters before the gases are released into the atmosphere (Yao et al., 2021). The generation of fly ash is heavily influenced by the type of coal used and the combustion technology employed. In traditional PCC systems, coal is ground into a fine powder and blown into the furnace, where it burns at high temperatures, typically ranging from 1,300°C to 1,700°C. This high-temperature combustion results in the formation of spherical fly ash particles that are rich in glassy aluminosilicate phases. The ash is then carried out of the boiler with the flue gases and captured using pollution control devices. One of the key factors that determine the characteristics of fly ash is the mineral content of the coal. During combustion, the organic matter in the coal is oxidized, leaving behind mineral residues that form fly ash. The exact composition of the fly ash depends on the mineralogy of the coal, the combustion temperature, and the efficiency of the pollution control equipment (Saikia et al., 2021). Fly ash typically consists of fine, powdery particles that are composed primarily of silica, alumina, and iron oxides, with smaller amounts of calcium, magnesium, and sulfur compounds.

1.3.2 Bio-Coal Combustion

Bio-coal, also known as bio-coal or torrefied biomass, is a renewable energy source that is produced by the thermal processing of biomass materials such as wood, agricultural residues, and organic waste. The torrefaction process involves heating the biomass in an oxygen-deprived environment at temperatures typically ranging from 200°C to 300°C. This process removes moisture and volatile compounds from the biomass, resulting in a solid fuel that is more energy-dense and has properties similar to traditional coal (Adeoye et al., 2023). Bio-coal briquettes are a sustainable energy source made from agricultural waste. These briquettes are created by compressing biomass such as cotton, maize, groundnut shells, etc. into dense blocks that can be burned as fuel. Unlike traditional coal, bio-coal is renewable and produces lower carbon emissions. It is an eco-friendly alternative that contributes to reducing the environmental impact of coal combustion. When bio-coal briquettes are burned, they generate fly ash, which can be used in various applications (Naik et al., 2023). This fly ash, known as bio-coal fly ash (BFA), has been studied for its potential in construction materials. Research has shown that BFA can mimic the properties of coal-based fly ash and can be used as a binder in geopolymer mortar. When mixed with materials like ground granulated blast furnace slag (GGBS) and activated by an alkaline solution, BFA can produce construction materials with high compressive strength. These materials, including bricks and paver blocks, offer a sustainable alternative to traditional cement-based products, reducing raw material consumption, carbon emissions, and environmental degradation. Bio-coal briquettes, therefore, represent a key component in the transition toward greener energy and construction practices. The combustion of bio-coal in thermal power plants generates fly ash in a manner similar to traditional coal. However, the composition and properties of BFA can differ significantly from those of coal fly ash due to the differences in the feedstock materials and the torrefaction process. Understanding these differences is essential for optimizing the use of BFA in industrial applications and for addressing potential environmental concerns.

1.4 DIFFERENCES IN FLY ASH GENERATED FROM BIO-COAL COMPARED TO TRADITIONAL COAL

The fly ash generated from the combustion of bio-coal differs from that produced by traditional coal in several key aspects, including chemical composition, particle size distribution, and environmental impact. These differences are primarily due to the nature of the biomass feedstock used to produce bio-coal and the conditions under which it is torrefied and combusted.

1.4.1 Chemical Composition

BFA generally has a higher content of unburned carbon compared to coal fly ash, which can affect its pozzolanic reactivity and suitability for use in cement and concrete applications (Li et al., 2023). The presence of higher levels of organic compounds in bio-coal feedstock contributes to the increased carbon content in the fly ash. Additionally, BFA may contain higher levels of potassium, phosphorus, and other elements derived from biomass, which can influence its behavior in industrial processes. Unlike coal fly ash, which is rich in silica and alumina, BFA ash may have a more varied composition depending on the type of biomass used. For example, fly ash from the combustion of woody biomass may have a higher silica content, while fly ash from agricultural residues may contain more calcium and potassium. These compositional differences can impact the performance of BFA in applications such as cement production, where consistency in chemical composition is important for maintaining product quality (Yao et al., 2015).

1.4.2 Particle Size Distribution

The particle size distribution of BFA can also differ from that of coal fly ash. BFA particles are generally larger and less spherical than those of coal fly ash, which can affect the workability and strength of concrete when used as a supplementary cementitious material (SCM) (Rawat and Kumar, 2022). The larger particle size of BFA may require adjustments to the mix design in concrete production to achieve the desired properties. The physical properties of BFA, such as surface area and particle shape, can also influence its performance in other industrial applications, such as soil stabilization and the production of building materials. For instance, the irregular shape and larger size of BFA particles may result in lower packing density and higher water demand in concrete mixtures, which could impact the overall strength and durability of the final product.

1.4.3 Environmental Impact

The environmental impact of BFA is generally considered to be lower than that of coal fly ash due to the renewable nature of the feedstock and the lower levels of toxic elements. However, the higher content of unburned carbon and organic compounds in BFA can pose challenges to its disposal and utilization. For example, the presence of high levels of unburned carbon can make BFA less suitable for use in certain applications, such as the production of high-performance concrete, where low carbon content is desired.

Additionally, BFA may have a higher nutrient content, such as potassium and phosphorus, which could make it suitable for use as a soil amendment or fertilizer. However, the variability in composition and the potential presence of heavy metals or other toxic elements necessitate thorough characterization and regulatory assessment before widespread agricultural application.

1.5 INDUSTRIAL APPLICATIONS OF FLY ASH

There have been multiple reports which illustrate industrial applications of fly ash. Figure 1.1 presents several pathways for utilizing fly ash, grouped into different industrial, agricultural, and environmental applications.

One of the most practical uses of fly ash is for mine filling. Fly ash can be used to fill abandoned or exhausted mines, providing structural support to prevent land subsidence and water pollution. Its fine texture and pozzolanic properties make it an ideal filler material, stabilizing voids in underground mines (Cao et al., 2022). Additionally, fly ash can help improve the geotechnical properties of the soil in mine areas, thus reclaiming the land for future use. The use of fly ash in mine filling helps

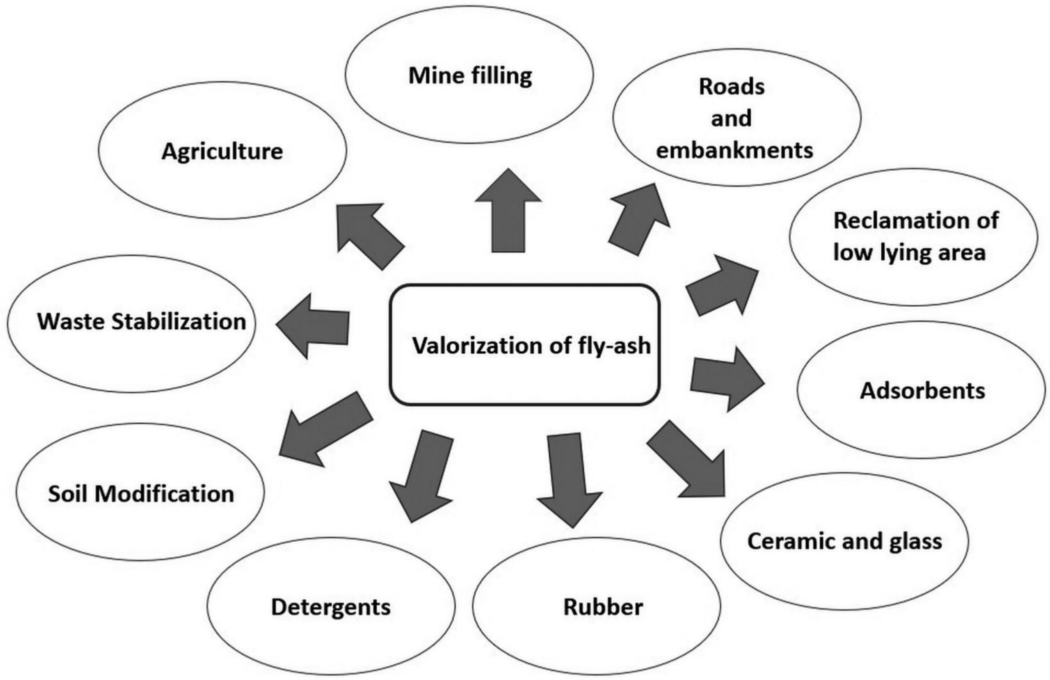

FIGURE 1.1 Valorization of fly ash in various industrial processes/practices to support circular economy.

to reduce the environmental hazards of abandoned mines, such as acid mine drainage and air pollution from fugitive dust. Fly ash is widely utilized in the construction of roads and embankments due to its excellent compaction and strength properties. When mixed with lime and water, fly ash forms a cementitious compound that can be used as a stabilizer in road base layers. This application enhances the durability and strength of roads, helping to reduce construction costs and material consumption. Fly ash is also used in the construction of embankments for highways, railways, and other infrastructure projects, providing a lightweight yet strong material that reduces the demand for natural aggregates and minimizes environmental degradation (Sahay and Bansal, 2022). Low-lying areas, especially in flood-prone regions, can benefit from the application of fly ash. Its lightweight and fine texture allow it to be used as a filling material to raise the ground level in areas susceptible to flooding. This helps in land reclamation and the prevention of waterlogging. Fly ash not only provides a cost-effective solution for filling low-lying areas but also contributes to mitigating land disposal issues by diverting fly ash from landfills. In addition, it improves the soil's physical properties, enhancing its suitability for future development or agricultural use.

Fly ash can also be processed into adsorbents for environmental applications. Due to its porous nature and chemical composition, fly ash can be modified to capture and remove pollutants from air, water, and wastewater. In water treatment, fly ash-based adsorbents are used to remove heavy metals, dyes, and organic contaminants. Similarly, in air purification, fly ash is employed to capture particulate matter (PM) and gaseous pollutants, contributing to pollution control efforts. The conversion of fly ash into adsorbents adds value to this waste material while addressing environmental challenges related to pollution. The ceramic and glass industries use fly ash as a raw material in the production of tiles, bricks, and other ceramic products. Fly ash contains silica and alumina, essential components in ceramic manufacturing, making it a suitable substitute for traditional clay. Moreover, the use of fly ash in glass production reduces the demand for virgin materials like sand and limestone (Zhang et al., 2022). The fly ash's fine texture and chemical stability ensure that ceramic and glass products maintain their strength and durability while promoting sustainability through resource conservation. Fly ash finds application in the rubber industry as a reinforcing filler. In the manufacturing of rubber products like tires and conveyor belts, fly ash is incorporated to enhance mechanical properties, such as tensile strength, abrasion resistance, and heat resistance. Using fly ash as a filler in rubber production reduces the consumption of other natural fillers like carbon black, which are more expensive and environmentally taxing to produce (Hoe-Woon et al., 2024). The incorporation of fly ash contributes to lowering production costs and the overall environmental footprint of the rubber industry. Another innovative use of fly ash is in the production of detergents. Fly ash can act as a filler and abrasive agent in detergent formulations, improving the cleaning properties of the detergent. It helps in the scrubbing action required for removing tough stains and serves as a bulking agent, reducing the need for more expensive raw materials. This application not only enhances the efficiency of detergents but also provides an outlet for large quantities of fly ash, further promoting waste reduction and resource optimization.

In agriculture, fly ash can be used to improve the structure and fertility of soils. Its addition to soil helps to increase water retention, reduce bulk density, and enhance aeration, which is beneficial for plant growth. Fly ash is also rich in essential nutrients like potassium, phosphorus, and trace elements, which contribute to soil fertility (Varshney et al., 2022). It has been effectively used to amend acidic soils by neutralizing their pH and improving their capacity to support crop production. Fly ash-based soil modification helps to enhance agricultural productivity while providing a sustainable use for this waste material (Hu et al., 2021). Fly ash is also employed in the stabilization of hazardous and non-hazardous waste. Its pozzolanic properties enable it to bind with other materials, encapsulating harmful substances and reducing their mobility. This is particularly useful in the treatment of industrial waste, sewage sludge, and contaminated soils. Fly ash is mixed with these wastes to form a stable, inert mass that prevents the leaching of contaminants into the environment. Waste stabilization with fly ash is a cost-effective and environmentally responsible way to manage hazardous waste and minimize its impact on ecosystems. Beyond soil modification, fly ash has broader applications in agriculture. It is used as a soil conditioner and fertilizer to improve soil structure and nutrient availability. Fly ash can enhance the cation exchange capacity of soils, allowing them to retain more nutrients and release them slowly to plants. Additionally, its use in composting can improve the decomposition process, producing nutrient-rich organic fertilizers. Fly ash also acts as a pest repellent when applied to crops, reducing the need for chemical pesticides. The use of fly ash in agriculture provides a sustainable alternative to chemical fertilizers, contributing to organic farming practices and environmental conservation.

1.6 FLY ASH VALORIZATION AND CIRCULAR ECONOMY

The uses of fly ash outlined in Figure 1.1 align closely with the principles of a circular economy, which aims to minimize waste and maximize resource efficiency by closing the loop on material usage through recycling, reuse, and regeneration. Here's how these applications contribute to the circular economy.

1.6.1 Waste Minimization and Resource Efficiency

Fly ash is typically considered a waste product generated from coal combustion in power plants. However, instead of disposing of it in landfills (a linear economy approach), valorizing fly ash allows it to be repurposed into valuable materials. This reduces the amount of waste that needs to be managed and helps conserve virgin resources like sand, lime, and clay. In the circular economy, the goal is to use materials for as long as possible. By converting fly ash into products like construction materials, adsorbents, ceramics, and soil conditioners, industries can extend the useful life of this material, contributing to the efficient use of available resources (Huang et al., 2022).

1.6.2 Reduction of Virgin Material Consumption

Using fly ash in roads and embankments, mine filling, and as a binder in geopolymer concrete reduces the need for virgin materials like cement, lime, and natural aggregates. Cement production, for example, is a significant source of greenhouse gas emissions, so substituting it with fly ash not only reduces the demand for raw cement but also helps mitigate environmental impacts like CO_2 emissions. In the ceramic and glass industries, fly ash serves as an alternative to natural raw materials, reducing the need to extract virgin sand, clay, and minerals. This substitution preserves natural resources and decreases the environmental degradation caused by mining (da Costa et al., 2022).

1.6.3 Closing the Loop Through Recycling and Reuse

Fly ash can be used in mine filling, helping to rehabilitate and reclaim land that has been mined, a key principle of the circular economy. This turns an environmental problem of unused fly ash and degraded land into a solution, restoring land for potential future use while safely disposing of industrial waste. The use of fly ash for waste stabilization ensures that hazardous waste is immobilized and safely contained, reducing the risk of environmental contamination. By incorporating fly ash into this process, industrial waste is repurposed in a way that prevents further pollution, thereby contributing to sustainable waste management.

1.6.4 Supporting Sustainable Agriculture

Fly ash can act as a soil conditioner or additive, improving soil fertility and structure. In agriculture, it enhances water retention, aeration, and nutrient availability, reducing the need for chemical fertilizers. This promotes more sustainable agricultural practices by utilizing fly ash as a renewable input rather than relying solely on synthetic fertilizers, which are resource-intensive to produce. By improving soil quality, fly ash helps regenerate soil ecosystems, a core principle of the circular economy. Fly ash is also used in composting to improve decomposition, which enhances organic matter recycling. This supports the circular economy by returning nutrients to the soil in a natural cycle.

1.6.5 Reducing Carbon Footprint

One of the major circular economy benefits is reducing the carbon footprint of construction materials. Using fly ash in the creation of geopolymer mortar or in replacing cement drastically reduces carbon emissions. Fly ash-based geopolymer concrete can cut CO_2 emissions by up to 80% compared to traditional Portland cement, supporting climate change mitigation efforts. In industries like ceramics, rubber, and glass, incorporating fly ash reduces the energy intensity and carbon emissions associated with processing virgin materials. The reuse of waste fly ash closes the loop in industrial cycles, reducing the need for energy-intensive raw material production (Kumar et al., 2022).

1.6.6 Innovative Material Recycling

The development of adsorbents from fly ash for water and air purification represents another example of upcycling waste materials into new, valuable products. These adsorbents can remove contaminants from industrial wastewater and reduce air pollution, contributing to environmental clean-up efforts and preventing additional waste. The use of fly ash as a filler in detergents not only reduces the need for synthetic chemical fillers but also provides a pathway for reusing industrial waste in everyday consumer products. This closes the loop by integrating waste materials into new supply chains (Al-Ghouti et al., 2021).

1.6.7 Fostering a Circular Industrial Ecosystem

The various uses of fly ash promote an industrial ecosystem where waste from one process (coal combustion) becomes a valuable input for other industries (construction, agriculture, manufacturing). This symbiotic relationship between different industries is a hallmark of the circular economy, where waste is minimized, and resource flows are optimized. Utilizing fly ash locally for construction, reclamation, and agriculture reduces transportation costs and energy use, contributing to localized circular economies. This also supports the development of industries that can process fly ash into useful products, creating new jobs and economic opportunities.

1.6.8 Extending Product Life Cycles

Many fly ash-based products, such as concrete, ceramics, and glass, have long life cycles, making them inherently more sustainable. Using fly ash in durable products extends the material's usefulness far beyond its original life as a combustion byproduct. This durability aligns with the circular economy goals of creating long-lasting materials that reduce the need for frequent replacement. The valorization of fly ash supports the circular economy by turning an abundant industrial byproduct into a resource that can be used across a wide range of industries, from construction to agriculture. By integrating fly ash into the production of roads, embankments, ceramics, soil conditioners, and more, we can reduce the demand for virgin materials, minimize waste, and decrease carbon emissions. This not only mitigates the environmental impact of fly ash disposal but also contributes to a more sustainable and resource-efficient industrial system. As industries continue to adopt circular economy practices, fly ash valorization will play an essential role in achieving zero-waste goals and transitioning toward more sustainable economic models (Tang et al., 2021).

1.7 ENVIRONMENTAL IMPACT AND SUSTAINABILITY

1.7.1 Environmental Concerns Associated with the Disposal of Coal Fly Ash

Fly ash disposal poses significant environmental challenges due to the large volumes generated by coal-fired power plants and the potential for harmful substances to leach into the environment. Coal fly ash contains various heavy metals and trace elements, such as arsenic, lead, mercury, and selenium, which can be toxic to both humans and wildlife. The improper disposal of fly ash can lead to contamination of soil and water resources, posing serious environmental and public health risks (Yao et al., 2015). One of the primary environmental concerns associated with fly ash disposal is the potential for leachate formation. When fly ash is disposed of in landfills or surface impoundments, rainwater or other moisture can percolate through the ash, leaching out heavy metals and other toxic substances. This leachate can then migrate into surrounding soil and groundwater, leading to contamination. Studies have shown that the leaching potential of fly ash is influenced by factors such as the chemical composition of the ash, the pH of the leachate, and the presence of other materials in the disposal site.

In addition to the risk of leachate formation, the disposal of fly ash in landfills or surface impoundments can also contribute to air pollution. Fine particles of fly ash can become airborne during handling, transportation, and disposal, leading to the release of PM into the atmosphere. These airborne particles can have serious health implications, particularly for individuals with respiratory conditions, as well as contribute to environmental issues such as haze and reduced visibility. Another significant environmental concern is the potential for the structural failure of fly ash disposal sites. In some cases, surface impoundments or ash ponds have failed, leading to catastrophic releases of fly ash into nearby waterways and ecosystems. One of the most notable incidents occurred in 2008, when the Tennessee Valley Authority's Kingston Fossil Plant in the United States experienced a massive ash spill, releasing over a billion gallons of coal ash slurry into the surrounding environment. This event highlighted the risks associated with fly ash disposal and the need for more stringent regulations and oversight (Li et al., 2021a, 2021b).

1.7.2 Strategies for Mitigating the Environmental Impact

Given the significant environmental risks associated with fly ash disposal, it is essential to implement strategies to mitigate these impacts and promote the safe and sustainable management of fly ash. Several approaches can be employed to reduce the environmental footprint of fly ash disposal and enhance its beneficial use.

1.7.2.1 Improved Landfill and Impoundment Design

One of the most effective ways to mitigate the environmental impact of fly ash disposal is to improve the design and operation of landfills and surface impoundments. This includes the use of liners and leachate collection systems to prevent the migration of contaminants into the soil and groundwater. Additionally, covering fly ash disposal sites with soil or synthetic materials can help reduce the risk of airborne PM and minimize the potential for erosion and surface runoff. Regular monitoring of fly ash disposal sites is also crucial for early detection of potential environmental issues. This includes monitoring groundwater quality, leachate composition, and air quality to ensure that any adverse effects are identified and addressed promptly. The use of advanced monitoring technologies, such as remote sensing and geophysical surveys, can enhance the ability to detect and respond to environmental risks associated with fly ash disposal (Chindaprasirt and Rattanasak, 2010).

1.7.2.2 Encapsulation and Solidification

Encapsulation and solidification are techniques used to stabilize fly ash and reduce its potential for leaching and airborne release. These methods involve mixing fly ash with binding agents, such as cement or lime, to form a solid, stable material that can be safely disposed of or used in construction applications. Encapsulation can significantly reduce the mobility of heavy metals and other contaminants in fly ash, thereby minimizing the risk of environmental contamination. In addition to reducing the environmental impact of fly ash disposal, encapsulation, and solidification can also enhance the potential for beneficial use of fly ash. For example, stabilized fly ash can be used as a construction material in road bases, embankments, and other infrastructure projects, providing a sustainable alternative to traditional materials.

1.7.2.3 Regulatory Frameworks and Guidelines

The implementation of robust regulatory frameworks and guidelines is essential for ensuring the safe management of fly ash and mitigating its environmental impact. Governments and environmental agencies have developed regulations governing the disposal, handling, and use of fly ash to protect public health and the environment. These regulations often include requirements for the design and operation of disposal sites, limits on permissible contaminant levels, and guidelines for the beneficial use of fly ash in various applications (Wang et al., 2020). In many countries, the classification of fly ash as either hazardous or non-hazardous waste determines the regulatory requirements for its disposal and use. For example, in the United States, the Environmental Protection Agency (EPA) has established regulations under the Resource Conservation and Recovery Act (RCRA) that classify coal combustion residuals (CCRs), including fly ash, as non-hazardous waste, subject to specific management standards. However, the classification of fly ash can vary depending on its chemical composition and the presence of hazardous substances.

1.7.2.4 Promoting Beneficial Use and Recycling

One of the most effective strategies for reducing the environmental impact of fly ash disposal is to promote its beneficial use and recycling in various industrial applications. By finding valuable uses for fly ash, such as in cement production, concrete manufacturing, and construction materials, the need for disposal is reduced, and the environmental footprint of coal-fired power plants is minimized (Wei et al., 2022). The beneficial use of fly ash not only reduces the volume of waste requiring disposal but also contributes to resource conservation and sustainability. For example, the use of fly ash in cement and concrete production reduces the demand for raw materials, such as limestone and clay, and lowers energy consumption and CO_2 emissions associated with the production of Portland cement. Additionally, the use of fly ash in construction applications can improve the durability and performance of infrastructure, extending its lifespan and reducing the need for maintenance and repairs.

1.8 SUSTAINABLE MANAGEMENT PRACTICES

1.8.1 Role of Fly Ash in Promoting Circular Economy Principles

The concept of a circular economy emphasizes the importance of resource efficiency, waste minimization, and the recycling and reuse of materials to create a closed-loop system that reduces environmental impact and promotes sustainability. Fly ash, as a byproduct of coal combustion, has the potential to play a significant role in advancing circular economy principles by serving as a valuable resource in various industrial processes.

1.8.1.1 Resource Efficiency and Waste Minimization

Fly ash contributes to resource efficiency by providing a secondary raw material that can replace virgin resources in industrial applications. For example, in the construction industry, fly ash can be used as a SCM in cement and concrete production, reducing the need for natural resources such as limestone, clay, and gypsum (Jin et al., 2023). The use of fly ash in this way not only conserves natural resources but also reduces the environmental impact of raw material extraction and processing. Waste minimization is another key aspect of the circular economy, and the beneficial use of fly ash is an effective way to achieve this goal. By finding valuable applications for fly ash, the need for disposal in landfills or surface impoundments is reduced, leading to a decrease in the environmental footprint of coal-fired power plants. This approach aligns with the principles of circular economy by turning a waste product into a valuable resource, thereby closing the loop and reducing the need for new raw materials.

1.8.1.2 Recycling and Reuse

Recycling and reuse are central components of the circular economy, and fly ash offers numerous opportunities for both. In addition to its use in cement and concrete production, fly ash can be recycled into a variety of other products, such as bricks, tiles, and lightweight aggregates. These recycled products can then be used in construction projects, reducing the demand for traditional building materials and contributing to a more sustainable built environment. The reuse of fly ash in environmental remediation is another important aspect of its role in the circular economy. Fly ash can be used to stabilize contaminated soils, neutralize acidic mine drainage, and encapsulate hazardous waste, providing a sustainable solution for managing environmental pollutants. By recycling fly ash in these applications, the need for new materials and resources is reduced, and the environmental impact of waste disposal is minimized.

1.8.2 Case Studies on Successful Fly Ash Utilization and Recycling

Several case studies demonstrate the successful utilization and recycling of fly ash, showcasing its potential to contribute to a circular economy and promote sustainability in various industries.

1.8.2.1 Cement and Concrete Production

The use of fly ash in cement and concrete production is one of the most well-established and successful examples of its beneficial use. In the United States, the production of blended cements containing fly ash has been widely adopted, particularly in large infrastructure projects such as highways, bridges, and dams. For example, the Hoover Dam, one of the most iconic infrastructure projects in the United States, incorporated large quantities of fly ash in its concrete mix, resulting in a more durable and resilient structure (Townsend et al., 2020). In India, the use of fly ash in cement production has gained momentum due to government regulations requiring the use of fly ash in certain construction projects. This has led to the widespread adoption of fly ash-based cements, known as Portland Pozzolana Cement (PPC), which offer improved durability and environmental performance compared to traditional Portland cement. The use of PPC in large-scale projects, such as the construction of highways and urban infrastructure, has demonstrated the benefits of fly ash utilization in reducing CO_2 emissions and promoting sustainable construction practices.

1.8.2.2 Geopolymer Technology

Geopolymers, which are synthesized from aluminosilicate materials such as fly ash, represent an innovative and sustainable alternative to traditional Portland cement. Several case studies highlight the successful use of fly ash-based geopolymers in construction and environmental remediation. For example, in Australia, fly ash-based geopolymers have been used to construct precast concrete elements for infrastructure projects, offering enhanced durability, chemical resistance, and reduced CO_2 emissions compared to conventional concrete. In addition to construction applications, fly ash-based geopolymers have been successfully used to encapsulate hazardous waste, providing a safe and stable solution for long-term waste management. The use of geopolymers in this context not only reduces the environmental impact of waste disposal but also promotes the circular economy by recycling fly ash into a valuable material for environmental protection (Naik et al., 2023).

1.8.2.3 Soil Stabilization and Land Reclamation

Fly ash has been successfully used in soil stabilization and land reclamation projects, providing a sustainable solution for improving soil properties and restoring degraded land. For example, in China, fly ash has been used to stabilize expansive soils in highway construction, reducing the risk of soil shrinkage and swelling, which can lead to structural damage. The use of fly ash in this application not only improves the durability and performance of the infrastructure but also promotes the reuse of industrial waste in environmentally beneficial projects. In the United Kingdom, fly ash has been used in land reclamation projects to restore former industrial sites and create new habitats for wildlife. By blending fly ash with soil and other materials, degraded land can be transformed into valuable green spaces, contributing to biodiversity conservation and sustainable land use. These case studies demonstrate the potential for fly ash to play a key role in sustainable land management and environmental restoration (Andavan and Pagadala, 2020).

Fly ash offers significant potential for promoting environmental sustainability and advancing circular economy principles through its beneficial use and recycling. By addressing the challenges of fly ash disposal and implementing strategies for its sustainable management, industries can reduce their environmental impact and contribute to a more sustainable future.

1.9 FUTURE PROSPECTS AND RESEARCH DIRECTIONS

1.9.1 Emerging Technologies and Research in the Utilization of Fly Ash

As the global focus shifts toward sustainability and resource efficiency, the utilization of fly ash is gaining renewed attention in various research and industrial applications. Emerging technologies are exploring innovative ways to harness the properties of fly ash, moving beyond traditional uses in cement and concrete production. These new approaches aim to enhance the value of fly ash and reduce its environmental footprint, contributing to more sustainable industrial practices.

1.9.1.1 Advanced Material Synthesis

One of the most promising areas of research is the use of fly ash in the synthesis of advanced materials, such as zeolites, ceramics, and nanomaterials. Zeolites, which are microporous aluminosilicate minerals, have a wide range of applications in catalysis, adsorption, and ion exchange. Researchers have developed methods to convert fly ash into zeolites through processes such as alkaline hydrothermal treatment. These fly ash-derived zeolites can be used in environmental applications, such as wastewater treatment and air purification, providing a valuable use for this industrial byproduct. Another innovative application is the use of fly ash in the production of ceramics and glass ceramics. Fly ash contains silica, alumina, and other oxides that can be sintered or melted to form ceramic materials. These ceramics can be used in construction, electronics, and other high-performance applications. The development of fly ash-based ceramics not only provides a sustainable alternative to traditional raw materials but also offers a way to recycle large volumes of fly ash, reducing the need for disposal. Nanotechnology is another emerging field where fly ash is being explored as a precursor material. Researchers are investigating the production of fly ash-based nanoparticles, such as silica nanoparticles, which have potential applications in coatings, adhesives, and composite materials. The development of nanomaterials from fly ash could open up new markets and applications, further enhancing the value of this byproduct (Li et al., 2021a, 2021b).

1.9.1.2 Carbon Capture and Storage

The role of fly ash in CCS technologies is another area of active research. Fly ash can be used as a sorbent material to capture carbon dioxide (CO_2) from flue gases in power plants and industrial processes. Researchers are developing methods to enhance the CO_2 capture capacity of fly ash through chemical modification and surface treatment. The captured CO_2 can then be stored in geological formations or used in various industrial applications, such as the production of carbonates or enhanced oil recovery (Provis and Bernal, 2014). The integration of fly ash in CCS technologies not only helps reduce greenhouse gas emissions but also provides a valuable use for fly ash, contributing to the circular economy. This approach aligns with global efforts to mitigate climate change and transition toward a low carbon economy.

1.9.1.3 Geopolymer Technology

As discussed earlier, geopolymer technology is an emerging area of research that leverages the pozzolanic properties of fly ash to produce environmentally friendly alternatives to Portland cement. Geopolymers are synthesized by activating fly ash with alkaline solutions, resulting in materials with excellent mechanical properties and chemical resistance. Researchers are exploring the use of fly ash-based geopolymers in various applications, including construction, waste encapsulation, and high-temperature materials (Naik et al., 2023). The development of geopolymer technology has the potential to revolutionize the construction industry by providing a sustainable alternative to traditional cement. Fly ash-based geopolymers offer significant environmental benefits, including lower CO_2 emissions, reduced energy consumption, and the recycling of industrial waste. As research in this area continues to advance, the adoption of geopolymers in large-scale construction projects is expected to increase.

1.9.2 Potential of Bio-Coal Fly Ash in Future Sustainable Practices

The growing interest in bio-coal as a renewable energy source has led to the generation of BFA, which presents unique opportunities for sustainable practices. BFA, derived from the combustion of biomass, has different chemical and physical properties compared to traditional coal fly ash, offering potential advantages in various applications.

1.9.2.1 Sustainable Construction Materials

BFA has the potential to be used as a sustainable alternative to traditional fly ash in the production of construction materials. Due to its lower carbon content and renewable origin, BFA can be used to produce greener concrete and cement with a reduced environmental footprint. Researchers are exploring the use of BFA in the synthesis of geopolymers, as well as its incorporation into blended cements and concrete mixes (Gil, 2022). The use of BFA in construction materials aligns with the principles of the circular economy by turning a renewable waste product into a valuable resource. As the demand for sustainable building materials continues to grow, BFA has the potential to play a key role in reducing the carbon footprint of the construction industry.

1.9.2.2 Agricultural Applications

Another promising area of research is the use of BFA in agriculture. BFA contains nutrients such as potassium, phosphorus, and calcium, which can be beneficial for soil health and crop growth. Researchers are investigating the use of BFA as a soil amendment or fertilizer, particularly in regions with nutrient-deficient soils. The application of BFA in agriculture could enhance soil fertility, reduce the need for chemical fertilizers, and promote sustainable farming practices. However, the use of BFA in agriculture requires careful consideration of its chemical composition, particularly the presence of heavy metals and other contaminants. Ongoing research is focused on assessing the environmental safety of BFA and developing guidelines for its use in agricultural applications.

1.9.2.3 Environmental Remediation

BFA also holds potential for use in environmental remediation, particularly in the stabilization and remediation of contaminated soils and water. The high surface area and reactive properties of BFA make it suitable for the adsorption and immobilization of heavy metals and other pollutants. Researchers are exploring the use of BFA in the treatment of industrial effluents, mine tailings, and contaminated land, offering a sustainable solution for managing environmental pollutants. The use of BFA in environmental remediation not only provides a valuable use for this byproduct but also contributes to the protection and restoration of ecosystems. As research in this area continues to evolve, BFA could become an important tool in sustainable environmental management.

1.10 POLICY AND REGULATORY FRAMEWORK

1.10.1 Overview of Existing Policies and Regulations Governing Fly Ash Management

The management of fly ash is subject to a complex regulatory framework that varies by region and is influenced by environmental, health, and safety considerations. Governments and environmental agencies have developed policies and regulations to ensure the safe disposal, handling, and beneficial use of fly ash, with the goal of minimizing its environmental impact and promoting sustainability.

1.10.1.1 United States

In the United States, the EPA plays a key role in regulating the management of CCRs, including fly ash. The EPA's regulations are governed by the RCRA, which classifies CCRs as non-hazardous waste, subject to specific management standards. These standards include requirements for the design and operation of disposal sites, groundwater monitoring, dust control, and the closure and post-closure care of disposal units (Kravchenko and Ruhl, 2021). In addition to federal regulations, states may implement their own rules governing fly ash management, which can be more stringent than federal requirements. The EPA also encourages the beneficial use of fly ash through initiatives such as the Coal Combustion Products Partnership (C2P2), which promotes the recycling of fly ash in construction and other applications.

1.10.1.2 European Union

The European Union (EU) has established a comprehensive regulatory framework for the management of fly ash under the Waste Framework Directive (2008/98/EC) and the Landfill Directive (1999/31/EC). The Waste Framework Directive classifies fly ash as waste and sets out requirements for its handling, treatment, and disposal, with an emphasis on promoting recycling and recovery. The Landfill Directive imposes strict limits on the disposal of fly ash in landfills, including requirements for landfill design, leachate management, and monitoring (Ummik et al., 2024). The EU also promotes the use of fly ash in construction through European standards (EN 450-1) (Adu-Amankwah et. al., 2016), which specifies the requirements for fly ash used as a component in concrete. This standard ensures that fly ash meets specific quality criteria, including limits on the content of harmful substances, to ensure its safe use in construction.

1.10.1.3 India

India has implemented a robust regulatory framework for fly ash management, driven by the country's rapid industrialization and the need to manage large volumes of fly ash generated by coal-fired power plants. The Ministry of Environment, Forest and Climate Change (MoEFCC) has issued several notifications under the environment Protection Act, 1986, mandating the use of fly ash in construction activities within a certain radius of coal-based power plants. These regulations aim to promote the utilization of fly ash in the production of cement, concrete, bricks, and other construction materials (Darmansyah et al., 2023). The MoEFCC's regulations also include provisions for the disposal of fly ash, requiring power plants to ensure the safe storage and disposal of fly ash in designated areas. The regulations encourage the reuse of fly ash in infrastructure projects, such as road construction and land reclamation, to minimize the need for disposal and promote resource efficiency.

1.10.2 Recommendations for Future Policy Directions

As the utilization of fly ash continues to evolve, there is a need for policies and regulations that can adapt to emerging technologies and practices while ensuring the protection of public health and the environment (Li et al., 2024). The following recommendations outline key areas for future policy development.

1.10.2.1 Harmonization of Standards

One of the challenges in fly ash management is the variability in standards and regulations across different regions. Harmonizing standards at the national and international levels would help ensure consistent quality and safety of fly ash used in various applications. This could involve the development of global guidelines for fly ash classification, quality control, and environmental testing, facilitating the trade and use of fly ash across borders.

1.10.2.2 Promotion of Research and Innovation

Governments and environmental agencies should promote research and innovation in the utilization of fly ash, particularly in emerging areas such as advanced materials, carbon capture, and environmental remediation. This could involve providing funding and incentives for research and development projects, as well as supporting pilot projects that demonstrate the feasibility and benefits of new technologies. By fostering innovation, policymakers can help unlock the full potential of fly ash in sustainable practices.

1.10.2.3 Encouragement of Circular Economy Practices

Policies should encourage the adoption of circular economy principles in fly ash management, emphasizing the recycling and reuse of fly ash in various industrial applications. This could include setting targets for the beneficial use of fly ash, providing incentives for companies that incorporate fly ash into their products, and establishing regulations that prioritize recycling over disposal. By promoting circular economy practices, policymakers can help reduce the environmental impact of fly ash and contribute to resource conservation.

1.10.2.4 Strengthening of Environmental Safeguards

As new uses for fly ash are developed, it is important to ensure that environmental safeguards keep pace with these innovations. This includes updating regulations to address the potential risks associated with new applications, such as the use of fly ash in agriculture or environmental remediation. Policymakers should also ensure that environmental impact assessments are conducted for large-scale fly ash utilization projects, to identify and mitigate any potential adverse effects on the environment and public health.

1.10.2.5 Global Collaboration and Knowledge Sharing

Finally, there is a need for greater global collaboration and knowledge sharing in fly ash management. This could involve the establishment of international forums or networks where policymakers, researchers, and industry stakeholders can exchange information and best practices. By working together, countries can learn from each other's experiences and develop more effective strategies for managing fly ash in a sustainable and environmentally responsible manner.

The future prospects for fly ash utilization are promising, with numerous opportunities for innovation and sustainability. However, realizing this potential will require ongoing research, the development of supportive policies, and a commitment to environmental stewardship. By adopting a forward-looking approach to fly ash management, industries and governments can contribute to a more sustainable future.

1.11 CONCLUSION TOP OF FORM

The role of fly ash, both from coal and bio-coal combustion, in industrial applications continues to evolve as a sustainable solution to waste management and resource efficiency. This chapter underscores the potential of fly ash, not just as a byproduct of industrial processes, but as a critical resource for innovations in construction, agriculture, and environmental remediation. The unique chemical properties of fly ash open doors for its use in a variety of industries, contributing to a circular economy by reducing waste and the consumption of virgin materials. In particular, BFA presents exciting possibilities due to its renewable nature, highlighting the importance of developing tailored strategies for its use. While the environmental benefits are evident, ongoing research and advancements in technology will further enhance the value of fly ash across industries. The transition from waste to resource aligns with global sustainability goals, and its integration into industrial systems holds significant promise for reducing environmental impacts while promoting industrial resilience. Through the continued exploration of its applications, fly ash is poised to play a pivotal role in advancing sustainable industrial practices.

REFERENCES

Adeoye, A. O., Lawal, O. S., Quadri, R. O., Malomo, D., Aliyu, M. T., Dang, G. E.,…, & Hikon, B. N. (2023). Sustainable energy via thermochemical and biochemical conversion of biomass wastes for biofuel production. In: Sharma, S.K., Upadhyay, R.K., Kumar, V., Valera, H. (eds) *Transportation Energy and Dynamics* (pp. 245–306). Singapore: Springer Nature Singapore.

Adu-Amankwah, S., Khatib, J. M., Searle, D. E., & Black, L. (2016). Effect of synthesis parameters on the performance of alkali-activated non-conformant EN 450 pulverised fuel ash. *Construction and Building Materials*, *121*, 453–459.

Al-Ghouti, M. A., Khan, M., Nasser, M. S., Al-Saad, K., & Heng, O. E. (2021). Recent advances and applications of municipal solid wastes bottom and fly ashes: Insights into sustainable management and conservation of resources. *Environmental Technology & Innovation*, *21*, 101267.

Alrefaei, Y., Wang, Y. S., & Dai, J. G. (2021). Effect of mixing method on the performance of alkali-activated fly ash/slag pastes along with polycarboxylate admixture. *Cement and Concrete Composites*, *117*, 103917.

Andavan, S., & Pagadala, V. K. (2020). A study on soil stabilization by addition of fly ash and lime. *Materials Today:* Proceedings, 22, 1125–1129.

Cao, H., Gao, Q., Zhang, X., & Guo, B. (2022). Research progress and development direction of filling cementing materials for filling mining in iron mines of China. *Gels*, *8*(3), 192.

Chindaprasirt, P., & Rattanasak, U. (2010). Utilization of blended fluidized bed combustion (FBC) ash and pulverized coal combustion (PCC) fly ash in geopolymer. *Waste Management*, *30*(4), 667–672.

da Costa, T. P., Quinteiro, P., Arroja, L., & Dias, A. C. (2022). Environmental performance of different end-of-life alternatives of wood fly ash by a consequential perspective. *Sustainable Materials and Technologies*, *32*, e00411.

Darmansyah, D., You, S. J., & Wang, Y. F. (2023). Advancements of coal fly ash and its prospective implications for sustainable materials in Southeast Asian countries: A review. *Renewable and Sustainable Energy Reviews*, *188*, 113895.

Fernández-Jiménez, A., & Palomo, A. (2003). Characterisation of fly ashes. Potential reactivity as alkaline cements. *Fuel, 82*(18), 2259–2265.

Gil, A. (2022). Challenges on waste-to-energy for the valorization of industrial wastes: Electricity, heat and cold, bioliquids and biofuels. *Environmental Nanotechnology, Monitoring & Management, 17,* 100615.

Hoe-Woon, T., Cheng-Yong, H., Yun-Ming, L., Qi-Hwa, N., Wei-Ken, P., Chin-Yii, Y.,…, & Yong-Jie, H. (2024). Assessing viability and leachability in fly ash geopolymers incorporated with rubber sludge. *Journal of Industrial and Engineering Chemistry*, 142, 499–511.

Hu, X., Huang, X., Zhao, H., Liu, F., Wang, L., Zhao, X., … & Ji, P. (2021). Possibility of using modified fly ash and organic fertilizers for remediation of heavy-metal-contaminated soils. *Journal of Cleaner Production*, *284*, 124713.

Huang, B., Gan, M., Ji, Z., Fan, X., Zhang, D., Chen, X.,…, & Fan, Y. (2022). Recent progress on the thermal treatment and resource utilization technologies of municipal waste incineration fly ash: A review. *Process Safety and Environmental Protection*, *159*, 547–565.

Jin, L., Chen, M., Wang, Y., Peng, Y., Yao, Q., Ding, J.,…, & Lu, S. (2023). Utilization of mechanochemically pretreated municipal solid waste incineration fly ash for supplementary cementitious material. *Journal of Environmental Chemical Engineering*, *11*(1), 109112.

Kravchenko, J., & Ruhl, L. S. (2021). Coal combustion residuals and health. In: Siegel, M., Selinus, O., Finkelman, R. (eds) *Practical Applications of Medical Geology*, 429–474.

Kumar, M., Prashant, S., & Kamath, M. V. (2022). Enhancing the sustainability of high strength concrete in terms of embodied energy and carbon emission by incorporating sewage sludge and fly ash. *Innovative Infrastructure Solutions*, *7*(4), 240.

Li, G., Hu, R., Hao, Y., Yang, T., Li, L., Luo, Z.,…, & Shen, G. (2023). CO_2 and air pollutant emissions from bio-coal briquettes. *Environmental Technology & Innovation*, *29*, 102975.

Li, W., Gu, K., Yu, Q., Sun, Y., Wang, Y., Xin, M.,…, & Zhang, D. (2021a). Leaching behavior and environmental risk assessment of toxic metals in municipal solid waste incineration fly ash exposed to mature landfill leachate environment. *Waste Management*, *120*, 68–75.

Li, X., Sun, Y., Li, W., Nie, Y., Wang, F., Bian, R.,…, & Lu, C. (2024). Solidification/stabilization pre-treatment coupled with landfill disposal of heavy metals in MSWI fly ash in China: A systematic review. *Journal of Hazardous Materials*, 478, 135479.

Li, Z., Fei, M. E., Huyan, C., & Shi, X. (2021b). Nano-engineered, fly ash-based geopolymer composites: an overview. *Resources, Conservation and Recycling, 168,* 105334.

Naik, S. S., Pandey, S., Pawar, S. N., Shinde, B. H., & Prakash, C. (2023). Innovative and interactive methodology for development of geopolymer mortar using fly ash of agricultural waste briquettes. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 18(8), 1–9.

Provis, J. L., & Bernal, S. A. (2015). Milestones in the analysis of alkali-activated binders. *Journal of Sustainable Cement-Based Materials*, *4*(2), 74–84.

Rawat, S., & Kumar, S. (2022). Critical review on processing technologies and economic aspect of bio-coal briquette production. *Preparative Biochemistry & Biotechnology*, *52*(8), 855–871.

Sahay, D. K., & Bansal, S. (2022). Use of fly ash—A resourceful byproduct in road embankment: A review. *Advances in Construction Materials and Sustainable Environment: Select Proceedings of ICCME 2020*, (LNCE,volume 196) 539–550.

Saikia, B. K., Hower, J. C., Islam, N., Sharma, A., & Das, P. (2021). Geochemistry and petrology of coal and coal fly ash from a thermal power plant in India. *Fuel*, *291*, 120122.

Tang, W., Pignatta, G., & Sepasgozar, S. M. (2021). Life-cycle assessment of fly ash and cenosphere-based geopolymer material. *Sustainability*, *13*(20), 11167.

Townsend, S. W., Spreadbury, C. J., Laux, S. J., Ferraro, C. C., Kari, R., & Townsend, T. G. (2020). Blending as a strategy for reusing municipal solid waste incinerator ash in road-base construction. *Journal of Environmental Engineering*, *146*(9), 04020106.

Ummik, M. L., Järvik, O., Reinik, J., & Konist, A. (2024). Ecotoxicity assessment of ashes from calcium-rich fuel combustion: contrasting results and regulatory implications. *Environmental Science and Pollution Research*, *31*(35), 48523–48533.

Varshney, A., Dahiya, P., Sharma, A., Pandey, R., & Mohan, S. (2022). Fly ash application in soil for sustainable agriculture: An Indian overview. *Energy, Ecology and E*nvironment, 7(4), 340–357.

Wang, N., Sun, X., Zhao, Q., Yang, Y., & Wang, P. (2020). Leachability and adverse effects of coal fly ash: A review. *Journal of Hazardous Materials*, *396*, 122725.

Wei, Y., Liu, S., Yao, R., Chen, S., Gao, J., & Shimaoka, T. (2022). Removal of harmful components from MSWI fly ash as a pretreatment approach to enhance waste recycling. *Waste Management*, *150*, 110–121.

Yao, X., Mao, J., Li, L., Sun, L., Xu, K., Ma, X.,…, & Xu, K. (2021). Characterization comparison of bottom ash and fly ash during gasification of agricultural residues at an industrial-scale gasification plant–Experiments and analysis. *Fuel*, *285*, 119122.

Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews, 141,* 105–121.

Zhang, Z., Li, Z., Yang, Y., Shen, B., Ma, J., & Liu, L. (2022). Preparation and characterization of fully waste-based glass-ceramics from incineration fly ash, waste glass and coal fly ash. *Ceramics International*, *48*(15), 21638–21647.