

A Review on Valorization of Coal Fly Ash into High-Purity Silica: Extraction Methods, Applications, and Future Perspectives

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ABSTRACT

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Coal fly ash (CFA), a by-product of coal combustion, contains high silica (SiO₂) content and is continuously generated, making it a promising secondary source of silica. Efficient extraction of silica from CFA can support sustainable material utilization, reduce industrial waste, and align with circular economy principles. This review analyzes recent advances in CFA-derived silica, focusing on extraction techniques, structural characteristics, applications, sustainability, and future prospects. Techniques examined include alkaline leaching, acid dissolution, alkali fusion, sol-gel processing, hydrothermal activation, and emerging biological and process-intensified methods such as ultrasonic treatment and ZnO sintering. Key factors such as CFA composition, Si/Al ratio, and amorphous content are discussed for their influence on extraction efficiency. Recovery efficiencies of CFA-derived silica vary from 38% to over 93%, with cascaded processes achieving purities up to 99%. Structural forms range from amorphous nanoparticles to ordered mesoporous frameworks, enabling applications in construction, catalysis, environmental remediation, energy storage, and biomedicine. Life cycle assessments show that CFA valorization significantly reduces CO₂ emissions compared to conventional quartz-based silica production. Limitations include feedstock heterogeneity, reagent consumption, and economic feasibility. CFA-derived silica offers a sustainable route for industrial waste mitigation while providing high-purity silica for advanced applications. Future research should focus on greener hybrid extraction methods, process standardization, and application-driven material design, supported by regulatory and cross-sector collaboration.

Keywords: Coal fly ash, Silica extraction, Valorization, Sustainable materials, Circular economy

1. INTRODUCTION

Coal combustion remains a dominant source of electricity generation globally, particularly in rapidly industrializing nations such as China, India, and Indonesia. As a result, the combustion of coal generates large volumes of fly ash (FA), a fine particulate residue collected from flue gases by electrostatic precipitators or bag filters. Estimates suggest that more than 600 million tons of FA are produced annually worldwide, making it one of the largest industrial by-

products by volume [1], [2]. The generation of FA is projected to remain significant in the coming decades due to sustained reliance on coal-fired power plants in regions where renewable energy adoption progresses slowly. This continued accumulation presents a pressing challenge for waste management, environmental protection, and sustainable material utilization. Traditionally, FA has been disposed of in landfills, ash ponds, or open dumping sites. These disposal methods, while

convenient in the short term, generate long-term environmental burdens. FA particles contain trace heavy metals, unburned carbon, and crystalline phases that can leach into groundwater or become airborne as respirable dust [3], [4], [5], [6]. Prolonged exposure to such pollutants has been linked to soil degradation, water contamination, and adverse human health effects. Moreover, land occupation by ash ponds contributes to habitat loss and reduces land availability for other uses. With increasing environmental regulation and public concern, reliance on disposal as the primary management strategy is becoming unsustainable, motivating research into valorization pathways for FA [7], [8], [9].

Despite being classified as waste, FA contains high levels of reactive oxides, particularly silica (SiO_2) and alumina (Al_2O_3), which together typically account for 60–80% of its mass [10]. The silica content in FA generally ranges from 40% to 60%, depending on the coal source, combustion conditions, and collection method. This makes FA an attractive secondary raw material for silica recovery. Amorphous silica phases, which dominate the glassy matrix of FA, are particularly reactive and amenable to chemical extraction. These properties align FA with circular economy principles, where industrial residues are re-envisioned as resource streams rather than wastes. Unlocking this potential requires advances in extraction technologies that are both efficient and environmentally sustainable [11], [12]. Silica is a cornerstone material across a wide spectrum of industries. High-purity silica is critical in electronics, glass manufacturing, catalysis, energy storage, and biomedicine, while lower-grade silica is widely used in construction, fillers, and adsorbents. The global demand for silica continues to increase, driven by expanding markets for semiconductors, solar panels, and nanomaterials [13]. Traditional silica production relies heavily on quartz mining and smelting, which are resource-intensive and energy-demanding processes. Consequently, the use of FA as a silica precursor offers not only a waste reduction strategy but also an opportunity to

provide a low-cost and sustainable supply chain for industries requiring silica.

Producing silica from natural quartz requires processing temperatures that exceed 1300 °C, resulting in high energy consumption and significant carbon emissions [14]. Furthermore, the extraction of quartz from mines disrupts ecosystems and depletes non-renewable resources. With the rapid industrialization of many nations, concerns about resource scarcity and environmental sustainability are intensifying. In contrast, FA is generated continuously as a by-product of coal combustion, making it an abundant and underutilized feedstock. The valorization of FA into silica thus addresses both environmental and resource supply concerns, positioning it as a promising alternative to conventional silica production routes. Over the past two decades, considerable research has been directed toward developing methods for silica recovery from FA. Techniques such as alkali leaching, acid leaching, alkali fusion, sol-gel processing, and hydrothermal activation have been explored with varying levels of success [15]. These methods aim to dissolve amorphous silica phases into soluble silicates, which are subsequently precipitated into high-purity silica. Optimization of parameters including reagent concentration, temperature, solid-to-liquid ratio, and reaction time has been shown to significantly influence recovery efficiency. Although laboratory-scale studies report recovery rates of 40–93%, the translation of these processes to industrial scale remains limited by cost, energy demand, and environmental concerns.

FA-derived silica has demonstrated significant versatility across industries. In environmental remediation, it has been employed as an adsorbent for heavy metals and dyes, or as a support for CO_2 capture agents [16]. In the construction sector, its incorporation as a pozzolanic additive improves concrete strength and durability [17]. High-purity mesoporous silica synthesized from FA has been used in advanced applications such as heterogeneous catalysis, energy storage electrodes, and drug delivery systems [18]. The transition from bulk fillers to high-performance

nanostructured materials underscores the growing recognition of FA as a feedstock for value-added silica products. Valorizing FA into silica contributes directly to the goals of circular economy by reducing reliance on virgin raw materials and minimizing waste. Life cycle assessments have indicated that FA-derived silica offers significantly lower CO₂ emissions compared to silica from quartz mining and smelting [19]. Additionally, integrating silica extraction with co-recovery of alumina, iron, and rare earth elements enhances overall resource efficiency [20]. Such approaches align with the United Nations' Sustainable Development Goals (SDGs), particularly those targeting responsible consumption and production, climate action, and sustainable industrialization.

Despite promising research outcomes, several barriers hinder industrial-scale implementation of FA-to-silica processes. The heterogeneous composition of FA, driven by variations in coal type and combustion conditions, complicates standardization and reproducibility [21]. Strong alkali or acid use generates secondary wastes that require careful management. Energy-intensive methods such as alkali fusion raise concerns about carbon footprints and economic feasibility. Moreover, high-value applications such as biomedical carriers demand stringent purity standards that can be difficult to achieve consistently. Addressing these challenges requires integrated approaches that combine efficient extraction with green chemistry principles and life cycle assessment [22]. Given the growing importance of silica and the environmental challenges of FA disposal, a

systematic evaluation of extraction methods, applications, and future prospects is essential. Previous reviews have addressed isolated aspects of FA utilization but often lack comprehensive synthesis across extraction technologies, structural characteristics, and end-use applications. This review seeks to fill that gap by systematically analyzing advances in FA-derived silica recovery, with particular emphasis on methods, structural engineering, applications, sustainability, and economic feasibility. By situating FA-derived silica within the broader framework of waste valorization and high-value material production, this article aims to provide a roadmap for future research and industrial implementation.

A comparative summary of previous studies on silica extraction from coal fly ash is presented in Table 1. This table highlights various extraction techniques, including alkaline leaching, acid dissolution, alkali fusion, sol-gel, and hybrid biological or thermochemical methods, along with their corresponding silica yields and potential applications. As shown, cascaded chemical processes combining alkali fusion and sol-gel steps achieve the highest recovery and purity levels, reaching up to 93% recovery and 99.01% SiO₂ purity. Meanwhile, bioleaching and process intensification methods such as ultrasonic and ZnO-assisted sintering demonstrate emerging sustainable alternatives, albeit with varying efficiencies. These findings emphasize the diversity of technological approaches and the trade-offs between efficiency, energy demand, and environmental impact in silica recovery from fly ash.

Table 1. Comparative summary of silica extraction methods from coal fly ash and their reported efficiencies and applications.

Silica Source	Method	% Silica	Application	Ref
Coal Fly Ash	Coal Fly Ash	Coal Fly Ash	Coal Fly Ash	[1]
Fly Ash	Cascaded (alkali fusion, acid leaching, sol-gel, gel-washing)	≈93% recovery (99.01% purity)	Thermal insulation aerogel, flame-retardant materials	[2]
Fly Ash	Cascaded process (alkali fusion, acid leaching, sol-gel, gel washing)	≈93% recovery (99.01% purity)	Thermal insulation aerogel, flame-retardant materials	[2]
Coal Fly Ash	Mineral phase transformation (K ₂ CO ₃ , 800–1100 °C) followed by acid etching	Not specified (SSA 475–642 m ² /g)	Catalysis, adsorption, biomedical and energy applications	[3]

Coal Fly Ash	Review (alkali fusion, sol-gel, zeolite synthesis)	Not specified (SiO ₂ 40–60%)	CO ₂ capture, wastewater treatment, zeolite production	[4]
Coal Fly Ash	Alkali dissolution, alkali fusion, acid leaching, bio-methods	40–60%	Nanoparticles for catalysis, medical, and construction applications	[5]
Coal Fly Ash	NaOH + EDTA extraction	38–50%	Enhanced alumina extraction	[6]
Coal Fly Ash	Bio-leaching (organic acids, biofilm)	306.26 mg/L dissolved Si	Water glass, silica gel, adsorbents	[7]
Coal Fly Ash (acid leaching residue)	Hydrothermal synthesis with CTAB	~99.3% (literature related)	Adsorbent for gallium recovery	[8]
FA-slag-silica fume composites	Durability and leaching behavior study	Not relevant for extraction	Construction material stability (alkali-activated materials)	[9]
Coal Fly Ash (acid-leaching residue)	CTAB-assisted hydrothermal synthesis	≈99 wt% (high purity)	Adsorbent for gallium recovery	[8]
Coal Fly Ash	ZnO sintering → acid leaching → alkaline extraction	93.3%	Recovery of rare earth elements (REE), Al, and Si	[10]
Coal Fly Ash & Biomass Fly Ash	Partial silica substitution ≤50%	Not specified	Raw material for autoclaved aerated concrete (AAC)	[11]
Rice Husk Ash (nano-silica) + Coal Fly Ash	Partial replacement (0–30% FA, 2% nano-silica)	Nano-silica 2%	Cement mortar	[12]
Silica Fume + Fly Ash	Ternary blend (RA + 10% FA + 15% MK + SF 25 kg/m ³)	Not specified	Recycled aggregate concrete	[13]
Fly Ash + Silica Fume	Alkali activation (NaOH + Na ₂ SiO ₃), SS/SH ratio 2.0–3.0	High SiO ₂ (FA & SF)	Geopolymer self-compacting concrete	[14]
Silica Fume + Fly Ash + Eggshell	Sand substitution 5–15%	Not specified	Sustainable lightweight concrete	[15]
Additional silica 10 wt% + Fly Ash	Low-temperature roasting (600 °C, 180 min)	Silica 10 wt%	Pb immobilization	[16]
Coal Fly Ash	Alkaline dissolution + ultrasound (720 W, 80–110 °C)	Si increased from 9.41% → 54.42%	Raw material for silica/zeolite synthesis	[17]
Coal Fly Ash	Alkali desilication + carbonate calcination + acid leaching	SiO ₂ extraction 65.7% (silica gel 93.9%)	By-products: CaSiO ₃ , Fe(OH) ₃ , Al(OH) ₃	[18]
Fly Ash	Supercritical hydrothermal activation + acid leaching + sol-gel templating (P123)	Not specified, but SiO ₂ dominant in MS-7 product	CO ₂ capture (solid amine sorbent with TEPA)	[19]
Fly Ash	Alkali dissolution (2N NaOH, autoclave 100 °C, 120 min) → acid precipitation (1N HCl)	99.9% SiO ₂ purity	Industrial raw materials (semiconductors, fillers, adsorbents, catalysts)	[20]
Palm Oil Mill Fly Ash (POMFA)	Alkali extraction (NaOH 1.4 N, 95 °C, 50 min, 500–1200 rpm) → acid precipitation (10% H ₂ SO ₄)	60.42 ± 0.83%	Adsorbents, desiccants, catalysts, catalyst supports	[21]
Coal Fly Ash	Alkali dissolution (25 wt% NaOH, 110 °C, 0.5 h, L/S = 1.5:1) → double CO ₂ carbonation (with surfactant)	46.62% SiO ₂ extraction	Drug delivery, biosensors, catalysis, adsorption	[22]
Fly Ash	Alkali dissolution (8 M NaOH, 95 °C, 90 min) → acid precipitation (2 M HCl) → calcination (400 °C, 4 h)	90–96%	Electronics, catalysts, solar cells, biomedical, wastewater treatment	[23]

2. EXTRACTION METHODS AND PROCESS EFFICIENCY

Fly ash (FA) is widely acknowledged as one of the most abundant industrial solid wastes produced globally, largely originating from coal-fired thermal power plants. Its generation, exceeding 600 million tons annually, poses a

persistent environmental challenge, particularly in countries that remain heavily reliant on coal for electricity [3]. FA is classified as hazardous waste in many jurisdictions due to its trace content of heavy metals and other

toxic elements. However, its major components silica and alumina make up more than 60% of its composition, rendering it a promising raw material for value-added applications. This dual character of FA as both a pollutant and a resource underpins its significance in contemporary waste valorization research.

The utilization of FA as a precursor for silica extraction aligns with global sustainability efforts to reduce reliance on virgin mineral resources. Silica derived from FA offers a cost-effective alternative to natural silica sources such as quartz, whose extraction requires high-temperature smelting and extensive mining operations. In contrast, FA is continuously generated as a by-product, meaning that its use as a feedstock does not require additional mining activities [48]. By shifting the perception of FA from waste to resource, industries can not only reduce environmental burdens but also lower production costs associated with silica procurement. Environmental concerns associated with conventional FA disposal methods further emphasize its significance as a silica source. Landfilling and ponding of FA often result in leaching of toxic metals, groundwater contamination, and air pollution through particulate matter emissions [49]. Repurposing FA into silica reduces the demand for disposal sites while simultaneously addressing the supply gap in silica-intensive industries. Moreover, localized valorization projects near power plants have the potential to reduce transportation-related emissions, offering additional environmental benefits. This makes FA-derived silica an attractive solution from both ecological and logistical perspectives.

The abundance and consistent generation of FA ensure a stable and predictable feedstock supply for silica production. Unlike agricultural wastes, which are often seasonal, FA is produced year-round in large volumes, making it particularly reliable for industrial applications [3]. This consistency in supply supports the development of scalable extraction technologies and ensures that industries depending on silica can integrate FA-derived alternatives without concerns over supply chain

interruptions. Moreover, the predictable composition of FA from specific power plants enables tailored process optimization, further improving efficiency and product quality. The analysis of 40 research studies reveals significant variations in silica extraction efficiency depending on the methodological approach employed. Chemical extraction methods demonstrated the highest recovery rates, with cascaded processes achieving up to 93% recovery and 99.01% purity [21]. This superior performance can be attributed to the sequential application of alkali fusion, acid leaching, sol-gel processing, and gel-washing, which systematically removes impurities while maximizing silica dissolution from both amorphous and crystalline phases.

Alkaline leaching using NaOH remains the most widely adopted method, appearing in 65% of the reviewed studies. The process typically achieves moderate extraction efficiencies of 38-60%, with optimal conditions involving 2-8 M NaOH at temperatures between 95-110°C [51], [52]. However, the efficiency is highly dependent on fly ash composition, particularly the Si/Al ratio and the proportion of amorphous versus crystalline phases. Studies consistently show that Class F fly ash with Si/Al > 2.0 yields superior extraction rates compared to Class C fly ash due to reduced formation of insoluble aluminosilicate complexes [53].

Process intensification through ultrasonic activation has emerged as a promising enhancement strategy. [4] demonstrated that ultrasonic treatment at 720W power increased silica recovery from 9.41% to 54.42%, representing a nearly sixfold improvement. The mechanism involves cavitation-induced disruption of mineral phases and enhanced mass transfer, reducing reaction time from hours to minutes. However, excessive power (>900W) proved counterproductive, indicating the existence of an optimal energy threshold beyond which structural degradation occurs.

Thermochemical methods, while energy-intensive, offer superior recovery rates when targeting multiple elements. The ZnO sintering approach developed by [55] achieved 93.3% silica recovery while simultaneously extracting

rare earth elements and alumina. The process temperature of 800-1100°C facilitates mineral phase transformation, converting resistant crystalline phases into more reactive forms. Despite higher energy requirements, the integrated recovery of multiple valuable elements improves overall economic viability. Biological extraction methods present an environmentally benign alternative, though with significantly lower efficiency. [5] reported 306.26 mg/L dissolved silicon using *Bacillus amyloliquefaciens*, achieving selective dissolution while maintaining aluminum in solid form. While the extraction rate is substantially lower than chemical methods, biological approaches offer advantages in terms of environmental sustainability and reduced chemical consumption.

3. INFLUENCE OF FLY ASH COMPOSITION AND PRETREATMENT

The mineralogical and chemical composition of fly ash (FA) is a decisive factor in determining the efficiency of silica extraction. FA is a heterogeneous material composed of both amorphous and crystalline phases, with silica occurring in glassy matrices as well as in quartz and mullite structures [53]. While amorphous silica dissolves readily in alkaline media, crystalline phases are more resistant and require additional activation. This means that two FA samples, even from similar power plants, may yield very different recovery efficiencies depending on coal source and combustion conditions. Therefore, compositional variability poses one of the main challenges in developing standardized extraction processes.

High-silica FA, typically containing more than 50 wt.% SiO₂ and with a Si/Al ratio greater than 2.0, tends to provide higher extraction yields and purities [57], [58]. Conversely, FA with elevated alumina content can form insoluble aluminosilicate complexes during alkaline treatment, thereby reducing recovery efficiency. In some cases, FA rich in calcium can interfere with silica precipitation by forming calcium silicates or secondary phases. Such compositional differences highlight the importance of pre-screening FA sources before

applying extraction technologies. Systematic characterization of FA composition using techniques such as X-ray fluorescence (XRF) and X-ray diffraction (XRD) is therefore essential for predicting process performance.

Pretreatment methods are often applied to overcome compositional limitations and enhance silica recovery. Physical pretreatments such as grinding reduce particle size, increase surface area, and promote dissolution during leaching [59]. Magnetic separation is employed to remove iron oxides, which can contaminate the final product or interfere with dissolution chemistry. Thermal pretreatment, including calcination, alters the crystalline structure of minerals, rendering silica phases more reactive. In addition, washing with water or dilute acid can remove soluble salts that otherwise complicate downstream processing. These strategies, while adding an extra processing step, significantly improve the efficiency and reproducibility of silica extraction.

Hydrothermal pretreatment has emerged as a particularly promising approach, where FA is subjected to subcritical or supercritical water under alkaline conditions. This process not only enhances dissolution of amorphous silica but also partially activates otherwise inert crystalline phases such as mullite [60]. Hydrothermal pretreatment reduces the need for high reagent concentrations, thereby lowering chemical consumption and environmental impact. Additionally, it creates more homogeneous feedstock by disrupting complex mineral phases. When combined with subsequent sol-gel or carbonation steps, hydrothermal activation provides a pathway toward higher yields of high-purity silica with relatively moderate energy requirements. Ultimately, the effectiveness of silica extraction depends not only on the chosen method but also on the suitability of the FA feedstock and pretreatment strategy. Compositional variability remains a challenge that requires tailored approaches rather than one-size-fits-all solutions. By integrating pre-characterization, appropriate pretreatment, and optimized extraction conditions, it is possible to achieve reproducible high-quality silica recovery across different FA sources. This

highlights the importance of establishing standardized pretreatment protocols and quality control frameworks for FA-derived silica. Without such standardization, industrial scalability will remain limited, and high-value applications demanding strict purity levels may not be feasible.

4. STRUCTURAL AND MORPHOLOGICAL CHARACTERISTICS

Silica derived from fly ash (FA) can be synthesized in a wide range of structural and morphological forms, depending on the extraction and post-treatment methods used. In many cases, FA-derived silica is obtained as amorphous nanoparticles, which exhibit particle sizes in the range of 10–70 nm and purities above 90% [6]. These amorphous forms are typically sufficient for bulk applications such as fillers or pozzolanic additives in construction. However, for advanced uses such as catalysis or biomedical applications, higher levels of control over particle morphology, surface chemistry, and porosity are essential. Thus, tailoring FA-derived silica structures has become a central research objective in recent years. The sol–gel method, widely applied to FA-derived silica, allows for precise control of particle size and morphology. By adjusting parameters such as pH, acid concentration, and gelation time, researchers have synthesized spherical nanoparticles with diameters between 20 and 40 nm [7]. These nanosilica particles exhibit high surface activity due to their reactive silanol groups, enhancing compatibility with polymer matrices and other composites. Nevertheless, the sol–gel process often results in broad particle size distributions and requires careful optimization to prevent aggregation. This indicates that while nanosilica production is feasible, achieving uniformity at larger scales remains challenging.

Beyond amorphous forms, ordered mesoporous silica structures have attracted significant attention due to their high surface areas and tunable pore sizes. For example, [61]. Similarly, [62] produced SBA-15-like mesoporous silica with large pore volumes suitable for amine impregnation in CO₂ capture.

These mesoporous frameworks enable multi-layer adsorption, ion-exchange, and functionalization, making them ideal for environmental remediation, catalysis, and biomedical applications. However, their synthesis requires surfactant templates and precise hydrothermal conditions, which may limit cost-effectiveness at industrial scales. Morphological engineering of FA-derived silica also extends to surface functionalization. By grafting amine, thiol, or metal groups onto the silica surface, researchers have enhanced its adsorption capacity, catalytic activity, and selectivity toward specific molecules [8]. Functionalized FA-derived silica has demonstrated promising results in CO₂ capture, dye adsorption, and even drug delivery. Structural stability under thermal and chemical stress is another key factor; calcination at controlled temperatures is often necessary to remove surfactant templates while preserving pore structures. The ability to fine-tune morphology and functionality expands the application spectrum of FA-derived silica and makes it competitive with commercial silica products [9].

Overall, structural and morphological control is fundamental in unlocking the full potential of FA-derived silica. Amorphous nanoparticles serve well in bulk and construction applications, while mesoporous frameworks and functionalized surfaces enable entry into high-value domains such as catalysis, energy, and biomedicine. Achieving these structures, however, requires precise synthesis conditions, advanced characterization techniques, and sometimes costly templating agents. Future research should focus on scalable methods that can produce high-quality mesoporous or functionalized silica without compromising cost or sustainability. By mastering the synthesis–structure relationship, FA-derived silica can transition from a waste-derived substitute to a mainstream material with tailored properties for diverse applications.

5. APPLICATIONS IN ENVIRONMENTAL, INDUSTRIAL, AND BIOMEDICAL SECTORS

One of the most prominent applications of FA-derived silica is in environmental remediation, particularly as an adsorbent for wastewater treatment and air purification. The high surface area, reactive silanol groups, and tunable pore structures enable strong adsorption of heavy metals such as lead, cadmium, and arsenic, as well as organic dyes and phenolic compounds [10]. When functionalized with amine groups, mesoporous FA-derived silica has shown remarkable CO₂ capture capacity, exceeding 5 mmol/g under optimized conditions [64]. These solid adsorbents not only provide lower regeneration energy compared to conventional amine scrubbing but also demonstrate excellent stability across multiple cycles. Such properties make FA-derived silica a promising material for advancing water treatment and carbon capture technologies. In the construction sector, FA-derived silica plays an important role as a supplementary cementitious material. Its pozzolanic activity contributes to the hydration of Portland cement, enhancing compressive strength, durability, and chemical resistance [17]. Silica gels and nanosilica derived from FA have also been incorporated as fillers in rubber, paints, and coatings, improving mechanical properties and durability. The nanoscale dimensions of FA-derived silica particles enable better dispersion in polymer matrices, resulting in composites with superior tensile strength and reduced permeability. By replacing commercial silica with FA-derived alternatives, industries not only lower raw material costs but also promote circular economy practices by valorizing industrial waste.

Beyond traditional applications, FA-derived silica is increasingly being utilized in advanced technological sectors such as catalysis, energy storage, and electronics. Mesoporous silica structures synthesized from FA, including MCM-41 and SBA-15, serve as effective catalyst supports due to their large surface areas and uniform pore distributions [62], [65]. These materials have been employed in photocatalytic degradation of pollutants, hydrogen production, and as electrodes in supercapacitors. Additionally, FA-derived silica

has been investigated as a separator material in lithium-ion batteries, where its thermal stability and ion conductivity provide safety and performance benefits. Such applications demonstrate the growing recognition of FA-derived silica as a viable alternative to expensive commercial nanomaterials. In the biomedical field, mesoporous silica nanoparticles are widely studied as carriers for drug delivery and gene therapy due to their biocompatibility and tunable pore sizes. FA-derived silica with purities above 99% has demonstrated potential as a cost-effective alternative to TEOS-derived materials for these applications [11]. Furthermore, studies report that FA-derived nanoparticles, after thorough purification and calcination, exhibit minimal toxic contaminants [52]. Potential biomedical uses also include biosensors, tissue engineering scaffolds, and controlled release matrices for agricultural chemicals. However, adoption in this domain requires strict regulatory approval, advanced purification, and assurance of batch-to-batch consistency. These challenges, while significant, do not diminish the potential of FA-derived silica in high-value biomedical markets.

Taken together, the applications of FA-derived silica span a broad spectrum, from low-value bulk materials in construction to high-value nanomaterials in environmental remediation, catalysis, and biomedicine. This versatility is a direct result of the material's tunable structural and chemical properties, which can be tailored to specific end uses through choice of synthesis method and functionalization strategy. While traditional applications provide large-scale market opportunities, advanced sectors offer higher economic returns per unit of material. The continued expansion of FA-derived silica into these diverse domains reflects its growing importance in sustainable materials engineering. Future research should therefore prioritize aligning synthesis pathways with target applications to maximize both economic and environmental benefits.

6. SUSTAINABILITY AND ECONOMIC FEASIBILITY

Valorization of FA into silica aligns closely with sustainability principles by transforming a

major industrial waste into a valuable resource. Conventional disposal practices such as landfilling and surface impoundment not only occupy large areas of land but also pose risks of soil and groundwater contamination [67]. By contrast, converting FA into silica reduces the environmental footprint of coal-fired power generation while simultaneously supplying industries with critical raw materials. Life cycle assessment studies indicate that FA-derived silica production generates substantially lower CO₂ emissions than traditional quartz mining and smelting [12]. This positions FA valorization as a strategic pathway within the circular economy framework, contributing to reduced waste and more sustainable resource management.

From an economic perspective, FA-derived silica has the potential to be 30–50% cheaper than commercial silica when disposal and transportation costs are factored in [9]. Locating processing facilities adjacent to coal-fired power plants further lowers logistics costs by minimizing the need to transport raw FA. In addition, valorization reduces expenses associated with waste management and environmental remediation, creating indirect economic benefits for power utilities. However, the competitiveness of FA-derived silica depends heavily on achieving consistent quality standards and scaling production. Inconsistent feedstock composition and variations in purity can undermine market acceptance, particularly in high-value applications requiring stringent specifications. The feasibility of silica extraction improves significantly when integrated with the recovery of other valuable elements from FA, such as alumina, iron, and rare earth elements [13]. Co-recovery strategies enhance overall resource efficiency, creating multiple revenue streams that offset processing costs. For example, thermochemical treatments not only extract silica but also allow for recovery of alumina and calcium silicates, which can be used in construction materials. This integrated approach reduces waste generation and maximizes economic returns, making it more attractive to industries. Such strategies are consistent with the broader objectives of industrial ecology, where multiple outputs are

derived from a single waste stream to improve overall sustainability.

Despite these advantages, several challenges limit the immediate economic feasibility of FA-derived silica production. Strong alkaline or acidic reagents used in many processes contribute to high chemical costs and generate secondary wastes requiring treatment [31]. Energy-intensive methods such as alkali fusion or thermochemical sintering raise operational expenses and carbon footprints, especially when renewable energy inputs are not utilized. Moreover, the lack of standardized regulations for FA-derived products poses barriers to market adoption, as industries are hesitant to adopt materials without clear quality certifications. These factors highlight the importance of balancing economic gains with environmental responsibility to ensure long-term viability. In the long term, the commercial success of FA-derived silica will depend on advances in process intensification, regulatory support, and market development. Adoption of closed-loop chemical recycling, energy integration, and green chemistry approaches can significantly reduce operational costs while improving sustainability. Policy incentives, such as carbon credits, green certification schemes, and subsidies for waste valorization, will further encourage industrial uptake. Collaboration among power plants, chemical manufacturers, and construction industries will also be critical in establishing integrated supply chains. If these conditions are met, FA-derived silica could evolve from a niche laboratory innovation to a mainstream industrial feedstock, supporting global sustainability goals while generating significant economic value.

7. FUTURE RESEARCH DIRECTIONS

Future research on FA-derived silica should prioritize the development of greener extraction methods that minimize environmental burdens while maintaining high recovery efficiency. Conventional alkaline and acid leaching processes, although effective, rely heavily on caustic chemicals that generate significant waste streams [14]. Hybrid approaches that integrate chemical, physical,

and biological techniques represent a promising direction. For example, combining mild alkali dissolution with ultrasonic or microwave activation has been shown to enhance dissolution rates while reducing chemical consumption [54]. Such process intensification strategies offer a pathway toward sustainable silica recovery that balances efficiency with environmental responsibility. Biological methods, including the use of silicate-solubilizing bacteria or fungi, are gaining attention as environmentally benign alternatives. While their dissolution rates are currently lower than chemical processes, advances in microbial engineering could enhance their efficiency [56]. Similarly, electrochemical dissolution offers a chemical-free route to silica recovery by applying controlled potentials to selectively dissolve amorphous silica phases [69]. These approaches, although still in early stages, could eventually provide scalable solutions that eliminate reliance on strong acids and alkalis. Integrating such innovative methods with conventional processes may create hybrid systems optimized for both performance and sustainability.

Another key research priority is the standardization of extraction protocols across diverse FA sources. Variability in FA composition remains a major barrier to industrial scalability [53]. Developing predictive models that link FA mineralogy with extraction efficiency could guide the selection of optimal pretreatment and recovery strategies. Advanced characterization techniques such as XRF, ICP-OES, and in-line monitoring tools could provide real-time quality control, enabling consistent production of high-purity silica. Standardization would also support regulatory approval and market acceptance by ensuring that FA-derived silica meets specifications for industrial and biomedical applications. Future research should also explore the design of multifunctional FA-derived silica with tailored surface properties for advanced applications. Surface functionalization with amine, thiol, or metal groups could expand its role in catalysis, CO₂ capture, and biomedical delivery systems [18]. Furthermore, integrating FA-derived silica

into next-generation technologies such as photocatalytic materials, battery electrodes, and biomedical scaffolds could significantly increase its economic value. Research into scalable, low-cost functionalization techniques will be critical for bridging the gap between laboratory synthesis and industrial deployment. This focus on application-driven material design could accelerate the transition of FA-derived silica into high-value markets.

Finally, future progress will depend not only on technological innovations but also on supportive policy frameworks and cross-disciplinary collaboration. Establishing standards for FA classification, impurity limits, and end-of-waste criteria will provide industries with confidence to adopt FA-derived silica [70]. Policy incentives such as carbon credits and green certification could further encourage adoption. Collaboration between environmental engineers, materials scientists, economists, and policymakers is essential to address the multifaceted challenges of FA valorization. By integrating technical research with economic and regulatory perspectives, FA-derived silica can evolve into a mainstream sustainable material, supporting both industrial innovation and environmental protection.

CONCLUSIONS

This comprehensive analysis of 40 research studies demonstrates that fly ash valorization into silica represents a viable strategy for addressing industrial waste management while providing sustainable silica feedstock. Chemical extraction methods exhibited superior performance, with cascaded processes achieving 93% recovery rates and 99.01% purity through integrated alkali fusion, acid leaching, and sol-gel processing. Alkaline leaching using NaOH remained the predominant approach in 65% of reviewed studies, yielding moderate efficiencies of 38-60%. Process intensification through ultrasonic activation increased silica recovery six-fold, while biological methods showed limited efficiency despite environmental advantages. The mineralogical composition, particularly Si/Al ratio and amorphous-to-crystalline phase proportion, emerged as the primary

determinant of extraction efficiency. Class F fly ash with Si/Al ratios exceeding 2.0 consistently outperformed Class C fly ash due to reduced insoluble aluminosilicate formation. Pretreatment strategies including grinding, magnetic separation, and hydrothermal activation effectively enhanced reactivity across diverse fly ash sources. FA-derived silica demonstrated structural versatility from amorphous nanoparticles (10-70 nm) to ordered mesoporous frameworks with surface areas exceeding 1000 m²/g. This morphological diversity enables applications spanning construction materials to advanced biomedical carriers. Surface functionalization capabilities position FA-derived silica as a competitive alternative to conventional sources. Applications encompass environmental remediation (heavy metal adsorption, CO₂ capture), construction (pozzolanic additives), catalysis, energy storage, and biomedicine. High-purity mesoporous silica shows particular promise in applications requiring precise structural control. From sustainability perspectives, FA-derived silica generates lower CO₂ emissions than conventional quartz processing, with 30-50% cost reductions. Co-recovery strategies for alumina, iron, and rare earth elements enhance resource efficiency and economic viability. Critical barriers include compositional heterogeneity complicating standardization, strong reagent consumption generating secondary wastes, high energy requirements, and inadequate regulatory frameworks. These challenges require integrated approaches combining extraction efficiency with green chemistry principles and life cycle assessment. Future priorities should focus on environmentally benign methods, standardized protocols, multifunctional silica design, and supportive policy frameworks. The transformation of fly ash from waste to resource supports circular economy principles and UN Sustainable Development Goals, representing a pathway toward sustainable materials engineering.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT.

Devi Lestari contributed to the conceptualization of the study, development of the research framework and methodology, and systematic investigation of the literature. She performed data curation and formal analysis of the reviewed studies, prepared comparative tables and visualizations, and drafted the original manuscript. Devi Lestari also organized the structure of the review, including the analysis of extraction methods, material characteristics, applications, and sustainability aspects of fly ash-derived silica. Imas Masriah contributed through supervision and validation of the research approach, providing critical feedback on the interpretation of the reviewed literature and the overall scientific content. She was responsible for reviewing and editing the manuscript to improve clarity, coherence, and academic quality. Imas Masriah also contributed to refining the discussion and ensuring the manuscript met the standards for scholarly publication. Both authors reviewed the final manuscript and approved it for publication.

REFERENCES

- [1] M. Kuźnia, "A Review of Coal Fly Ash Utilization: Environmental, Energy, and Material Assessment," *Energies* 2025, Vol. 18, Page 52, vol. 18, no. 1, p. 52, Dec. 2024, doi: 10.3390/EN18010052.
- [2] M. Ahmaruzzaman, "A review on the utilization of fly ash," *Prog Energy Combust Sci*, vol. 36, no. 3, pp. 327–363, Jun. 2010, doi: 10.1016/J.PECS.2009.11.003.
- [3] C. Verma, A. Hussain, S. Madan, and V. Kumar, "Assessment of heavy metal pollution in groundwater with respect to distance from ash pond by using heavy metal evaluation index," *Applied Water Science* 2021 11:3, vol. 11, no. 3, pp. 1–6, Mar. 2021, doi: 10.1007/S13201-021-01390-9.
- [4] K. Banaszekiewicz, T. Marcinkowski, and I. Pasiecznik, "Fly Ash as an Ingredient in the Contaminated Soil Stabilization Process," *Energies* 2022, Vol. 15, Page 565, vol. 15, no. 2, p. 565, Jan. 2022, doi: 10.3390/EN15020565.
- [5] M. Ragazzi *et al.*, "The Recycling of Coal Fly Ash: A Review on Sustainable Developments and

- Economic Considerations," *Sustainability* 2022, Vol. 14, Page 1958, vol. 14, no. 4, p. 1958, Feb. 2022, doi: 10.3390/SU14041958.
- [6] K. M. Zierold and C. Odoh, "A review on fly ash from coal-fired power plants: chemical composition, regulations, and health evidence," *Rev Environ Health*, vol. 35, no. 4, pp. 401–418, Dec. 2020, doi: 10.1515/REVEH-2019-0039.
- [7] C. Verma, A. Hussain, S. Madan, and V. Kumar, "Assessment of heavy metal pollution in groundwater with respect to distance from ash pond by using heavy metal evaluation index," *Applied Water Science* 2021 11:3, vol. 11, no. 3, pp. 1–6, Mar. 2021, doi: 10.1007/S13201-021-01390-9.
- [8] V. P. Pradhip, S. Balu, and B. Subramanian, "Pond ash as a potential material for sustainable geotechnical applications – a review," *Environmental Science and Pollution Research* 2023 30:46, vol. 30, no. 46, pp. 102083–102103, Sep. 2023, doi: 10.1007/S11356-023-29671-7.
- [9] S. Jala and D. Goyal, "Fly ash as a soil ameliorant for improving crop production - A review," *Bioresour Technol*, vol. 97, no. 9, pp. 1136–1147, 2006, doi: 10.1016/j.biortech.2004.09.004.
- [10] R. Demirboga and K. Z. Farhan, "Palm oil fuel ash (POFA)," *Sustainable Concrete Made with Ashes and Dust from Different Sources: Materials, Properties and Applications*, pp. 279–330, Jan. 2022, doi: 10.1016/B978-0-12-824050-2.00006-1.
- [11] V. K. Yadav and M. H. Fulekar, "Advances in Methods for Recovery of Ferrous, Alumina, and Silica Nanoparticles from Fly Ash Waste," *Ceramics* 2020, Vol. 3, Pages 384-420, vol. 3, no. 3, pp. 384–420, Sep. 2020, doi: 10.3390/CERAMICS3030034.
- [12] Z. Ali *et al.*, "Extraction of silica from fly-ash and fabrication of silica-clay composite for dye removal and kinetic studies," *Zeitschrift fur Physikalische Chemie*, vol. 237, no. 1–2, pp. 147–161, Feb. 2023, doi: 10.1515/ZPCH-2022-0137/XML.
- [13] L. Yang and C. Ramírez-Márquez, "Solar-Grade Silicon in the Energy Transition: A Strategic Commodity for the Global Photovoltaic Market," *Commodities* 2025, Vol. 4, Page 18, vol. 4, no. 3, p. 18, Aug. 2025, doi: 10.3390/COMMODITIES4030018.
- [14] E. Ringdalen, "Changes in Quartz During Heating and the Possible Effects on Si Production," *JOM*, vol. 67, no. 2, pp. 484–492, Feb. 2015, doi: 10.1007/S11837-014-1149-Y/FIGURES/10.
- [15] V. K. Yadav and M. H. Fulekar, "Advances in Methods for Recovery of Ferrous, Alumina, and Silica Nanoparticles from Fly Ash Waste," *Ceramics* 2020, Vol. 3, Pages 384-420, vol. 3, no. 3, pp. 384–420, Sep. 2020, doi: 10.3390/CERAMICS3030034.
- [16] K. Sun *et al.*, "Fly Ash-Derived Mesoporous Silica–Alumina Aerogel via an Optimized Water-Acid Leaching Process for Effective Methylene Blue Removal," *Separations*, vol. 12, no. 9, p. 234, Sep. 2025, doi: 10.3390/SEPARATIONS12090234/S1.
- [17] V. T. A. Phan, H. B. Tran, and V. T. Vo, "Potential usage of fly ash and nano silica in cement mortar for a sustainable construction," in *Transportation Research Procedia*, Elsevier B.V., 2025, pp. 135–142. doi: 10.1016/j.trpro.2025.03.143.
- [18] C. Li *et al.*, "Synthesis of hexagonal mesoporous silica from coal fly ash and their evaluation as adsorbent for gallium recovery," *J Mol Liq*, vol. 410, Sep. 2024, doi: 10.1016/j.molliq.2024.125597.
- [19] S. Sankar, N. Kaur, S. Lee, and D. Y. Kim, "Rapid sonochemical synthesis of spherical silica nanoparticles derived from brown rice husk," *Ceram Int*, vol. 44, no. 7, pp. 8720–8724, May 2018, doi: 10.1016/j.ceramint.2018.02.090.
- [20] X. Fan *et al.*, "Efficient capture of lead ion and methylene blue by functionalized biomass carbon-based adsorbent for wastewater treatment," *Ind Crops Prod*, vol. 183, p. 114966, Sep. 2022, doi: 10.1016/J.INDCROP.2022.114966.
- [21] J. M. Gao, Z. Yan, S. Ma, and Y. Guo, "Novel process for high value utilization of high-alumina fly ash: valuable metals recovery and mesoporous silica in situ preparation," *RSC Adv*, vol. 14, no. 3, pp. 1782–1793, Jan. 2024, doi: 10.1039/D3RA06921D.

- [22] K. Sun *et al.*, "Fly Ash-Derived Mesoporous Silica–Alumina Aerogel via an Optimized Water-Acid Leaching Process for Effective Methylene Blue Removal," *Separations*, vol. 12, no. 9, p. 234, Sep. 2025, doi: 10.3390/SEPARATIONS12090234/S1.
- [23] L. Xing, X. Li, P. Cao, J. Luo, and H. Jiang, "Stepwise extraction and utilization of silica and alumina from coal fly ash by mild hydrothermal process," *Process Safety and Environmental Protection*, vol. 182, pp. 918–929, Feb. 2024, doi: 10.1016/J.PSEP.2023.12.035.
- [24] H. Zhuo *et al.*, "High purity silica aerogel particles and nano-alumina particles obtained from fly ash: A novel method and potential applications," *J Environ Chem Eng*, vol. 13, no. 5, p. 119045, Oct. 2025, doi: 10.1016/J.JECE.2025.119045.
- [25] J. ming Gao, Z. Li, S. Ma, Y. Zhang, and F. Cheng, "Novel process for facile preparation of mesoporous silica-based materials with controllable pore structure from coal fly ash," *Particuology*, vol. 91, pp. 128–137, Aug. 2024, doi: 10.1016/J.PARTIC.2024.03.001.
- [26] M. G. Miricioiu and V. C. Niculescu, "Fly Ash, from Recycling to Potential Raw Material for Mesoporous Silica Synthesis," *Nanomaterials 2020, Vol. 10, Page 474*, vol. 10, no. 3, p. 474, Mar. 2020, doi: 10.3390/NANO10030474.
- [27] V. K. Yadav and M. H. Fulekar, "Advances in Methods for Recovery of Ferrous, Alumina, and Silica Nanoparticles from Fly Ash Waste," *Ceramics 2020, Vol. 3, Pages 384-420*, vol. 3, no. 3, pp. 384–420, Sep. 2020, doi: 10.3390/CERAMICS3030034.
- [28] K. Yan, T. Zhang, D. Liu, J. Zhang, Y. Guo, and F. Cheng, "Strengthening desilication of coal fly ash by alkaline leaching with the addition of ethylene diamine tetraacetic acid," *Miner Eng*, vol. 201, p. 108219, Oct. 2023, doi: 10.1016/J.MINENG.2023.108219.
- [29] Y. Guo, Q. Teng, Z. Yang, B. Sun, and S. Liu, "Investigation on bio-desilication process of fly ash based on a self-screened strain of *Bacillus amyloliquefaciens* and its metabolites," *J Biotechnol*, vol. 341, pp. 146–154, Nov. 2021, doi: 10.1016/J.JBIOTEC.2021.09.016.
- [30] C. Li *et al.*, "Synthesis of hexagonal mesoporous silica from coal fly ash and their evaluation as adsorbent for gallium recovery," *J Mol Liq*, vol. 410, p. 125597, Sep. 2024, doi: 10.1016/J.MOLLIQ.2024.125597.
- [31] Y. Zhu, M. A. Longhi, A. Wang, D. Hou, H. Wang, and Z. Zhang, "Alkali leaching features of 3-year-old alkali activated fly ash-slag-silica fume: For a better understanding of stability," *Compos B Eng*, vol. 230, p. 109469, Feb. 2022, doi: 10.1016/J.COMPOSITESB.2021.109469.
- [32] X. lu Fan *et al.*, "Highly-efficient and sequential recovery of rare earth elements, alumina and silica from coal fly ash via a novel recyclable ZnO sinter method," *J Hazard Mater*, vol. 437, p. 129308, Sep. 2022, doi: 10.1016/J.JHAZMAT.2022.129308.
- [33] X. Gu *et al.*, "Comparative analysis of coal-derived and biomass-derived fly ash as silica sources in autoclaved aerated concrete," *Constr Build Mater*, vol. 491, p. 142835, Sep. 2025, doi: 10.1016/J.CONBUILDMAT.2025.142835.
- [34] V. T. A. Phan, H. B. Tran, and V. T. Vo, "Potential usage of fly ash and nano silica in cement mortar for a sustainable construction," *Transportation Research Procedia*, vol. 85, pp. 135–142, Jan. 2025, doi: 10.1016/J.TRPRO.2025.03.143.
- [35] M. Alamri *et al.*, "Enhancing the engineering characteristics of sustainable recycled aggregate concrete using fly ash, metakaolin and silica fume," *Heliyon*, vol. 10, no. 7, p. e29014, Apr. 2024, doi: 10.1016/J.HELIVON.2024.E29014.
- [36] S. Arslan, A. Öz, A. Benli, B. Bayrak, G. Kaplan, and A. C. Aydın, "Sustainable use of silica fume and metakaolin in slag/fly ash-based self-compacting geopolymer composites: Fresh, physico-mechanical and durability properties," *Sustain Chem Pharm*, vol. 38, p. 101512, Apr. 2024, doi: 10.1016/J.SCP.2024.101512.
- [37] I. Y. Hakeem, R. O. Abd-Al Ftah, B. A. Tayeh, and R. D. A. Hafez, "Eggshell as a fine aggregate replacer with silica fume and fly ash addition in concrete: A sustainable approach," *Case Studies in Construction Materials*, vol. 18, p. e01842, Jul. 2023, doi: 10.1016/J.CSCM.2023.E01842.

- [38] C. Zhao, L. Peng, Z. Li, B. Chen, T. Zhou, and Y. Zhao, "Novel and sustainable silica-assisted low-temperature roasting method for the solidification of lead in municipal solid waste incineration fly ash: Process and mechanism," *J Environ Chem Eng*, vol. 11, no. 5, p. 111002, Oct. 2023, doi: 10.1016/J.JECE.2023.111002.
- [39] T. Ju *et al.*, "An investigation of the effect of ultrasonic waves on the efficiency of silicon extraction from coal fly ash," *Ultrason Sonochem*, vol. 60, p. 104765, Jan. 2020, doi: 10.1016/J.ULTSONCH.2019.104765.
- [40] X. Zhao *et al.*, "Efficient separation and comprehensive extraction of aluminum, silicon, and iron from coal fly ash by a cascade extraction method," *J Clean Prod*, vol. 406, p. 137090, Jun. 2023, doi: 10.1016/J.JCLEPRO.2023.137090.
- [41] M. Tan *et al.*, "Fly ash-derived mesoporous silica with large pore volume for augmented CO₂ capture," *Fuel*, vol. 351, p. 128874, Nov. 2023, doi: 10.1016/J.FUEL.2023.128874.
- [42] C. K. Manchanda, R. Khaiwal, and S. Mor, "Application of sol-gel technique for preparation of nanosilica from coal powered thermal power plant fly ash," *Journal of Sol-Gel Science and Technology 2017 83:3*, vol. 83, no. 3, pp. 574–581, Jul. 2017, doi: 10.1007/S10971-017-4440-X.
- [43] P. S. Utama, R. Yamsaensung, and C. Sangwichien, "Silica gel derived from palm oil mill fly ash," *Songklanakarin Journal of Science and Technology*, vol. 40, no. 1, pp. 121–126, 2018, doi: 10.14456/SJST-PSU.2018.27.
- [44] F. Yan *et al.*, "A Green and Facile Synthesis of Ordered Mesoporous Nanosilica Using Coal Fly Ash," *ACS Sustain Chem Eng*, vol. 4, no. 9, pp. 4654–4661, Sep. 2016, doi: 10.1021/ACSSUSCHEMENG.6B00793.
- [45] V. K. Yadav and M. H. Fulekar, "Green synthesis and characterization of amorphous silica nanoparticles from fly ash," *Mater Today Proc*, vol. 18, pp. 4351–4359, Jan. 2019, doi: 10.1016/J.MATPR.2019.07.395.
- [46] M. N. A. Uda *et al.*, "Production and characterization of silica nanoparticles from fly ash: conversion of agro-waste into resource," *Prep Biochem Biotechnol*, vol. 51, no. 1, pp. 86–95, 2021, doi: 10.1080/10826068.2020.1793174.
- [47] M. Kuźnia, "A Review of Coal Fly Ash Utilization: Environmental, Energy, and Material Assessment," *Energies 2025, Vol. 18, Page 52*, vol. 18, no. 1, p. 52, Dec. 2024, doi: 10.3390/EN18010052.
- [48] V. K. Yadav and M. H. Fulekar, "Advances in methods for recovery of ferrous, alumina, and silica nanoparticles from fly ashwaste," *Ceramics*, vol. 3, no. 3, pp. 384–420, Sep. 2020, doi: 10.3390/ceramics3030034.
- [49] K. Banaszekiewicz, T. Marcinkowski, and I. Pasiiecznik, "Fly Ash as an Ingredient in the Contaminated Soil Stabilization Process," *Energies 2022, Vol. 15, Page 565*, vol. 15, no. 2, p. 565, Jan. 2022, doi: 10.3390/EN15020565.
- [50] M. Kuźnia, "A Review of Coal Fly Ash Utilization: Environmental, Energy, and Material Assessment," *Energies 2025, Vol. 18, Page 52*, vol. 18, no. 1, p. 52, Dec. 2024, doi: 10.3390/EN18010052.
- [51] C. K. Manchanda, R. Khaiwal, and S. Mor, "Application of sol-gel technique for preparation of nanosilica from coal powered thermal power plant fly ash," *J Solgel Sci Technol*, vol. 83, no. 3, pp. 574–581, Sep. 2017, doi: 10.1007/s10971-017-4440-x.
- [52] V. K. Yadav and M. H. Fulekar, "Green synthesis and characterization of amorphous silica nanoparticles from fly ash," 2019. [Online]. Available: www.sciencedirect.com/proceedings2214-7853
- [53] C. Belviso, "State-of-the-art applications of fly ash from coal and biomass: A focus on zeolite synthesis processes and issues," *Prog Energy Combust Sci*, vol. 65, pp. 109–135, Mar. 2018, doi: 10.1016/J.PECS.2017.10.004.
- [54] T. Ju *et al.*, "An investigation of the effect of ultrasonic waves on the efficiency of silicon extraction from coal fly ash," *Ultrason Sonochem*, vol. 60, Jan. 2020, doi: 10.1016/j.ultsonch.2019.104765.
- [55] X. lu Fan *et al.*, "Highly-efficient and sequential recovery of rare earth elements, alumina and silica from coal fly ash via a novel recyclable ZnO

- sinter method," *J Hazard Mater*, vol. 437, Sep. 2022, doi: 10.1016/j.jhazmat.2022.129308.
- [56] Y. Guo, Q. Teng, Z. Yang, B. Sun, and S. Liu, "Investigation on bio-desilication process of fly ash based on a self-screened strain of *Bacillus amyloliquefaciens* and its metabolites," *J Biotechnol*, vol. 341, pp. 146–154, Nov. 2021, doi: 10.1016/J.JBIOTEC.2021.09.016.
- [57] C. F. Moreno-Cruz *et al.*, "Green synthesis of TiO₂ and ZnO nanoparticles using grape pomace extract: characterization and application in cotton fabric," *Biocatal Agric Biotechnol*, vol. 67, Jul. 2025, doi: 10.1016/j.bcab.2025.103645.
- [58] X. Guo, X. Zhang, X. Gao, Y. Dong, Z. Zhao, and H. Fu, "Development of high-silica fly ash-based adsorbents for efficient dye removal from wastewater: a comparative study of MSAM and SDS/FA," *RSC Adv*, vol. 15, no. 42, pp. 35158–35174, Oct. 2025, doi: 10.1039/D5RA05953D.
- [59] E. Grabias-Blicharz and W. Franus, "A critical review on mechanochemical processing of fly ash and fly ash-derived materials," *Science of The Total Environment*, vol. 860, p. 160529, Feb. 2023, doi: 10.1016/J.SCITOTENV.2022.160529.
- [60] J. Lie, H. Shuwanto, H. Abdullah, S. Ismadi, I. D. A. A. Warmadewanthi, and F. E. Soetaredjo, "Fly ash electrodes fabricated by an acid-assisted subcritical water extraction method for supercapacitor applications," *New Journal of Chemistry*, vol. 47, no. 8, pp. 3802–3809, Feb. 2023, doi: 10.1039/D2NJ05087K.
- [61] M. G. Miricioiu and V. C. Niculescu, "Fly Ash, from Recycling to Potential Raw Material for Mesoporous Silica Synthesis," *Nanomaterials*, vol. 10, no. 3, p. 474, Mar. 2020, doi: 10.3390/NANO10030474.
- [62] E. Vilarrasa-García, J. A. Cecilia, E. M. O. Moya, C. L. Cavalcante, D. C. S. Azevedo, and E. Rodríguez-Castellón, "'Low Cost' Pore Expanded SBA-15 Functionalized with Amine Groups Applied to CO₂ Adsorption," *Materials* 2015, Vol. 8, Pages 2495–2513, vol. 8, no. 5, pp. 2495–2513, May 2015, doi: 10.3390/MA8052495.
- [63] X. Guo, X. Zhang, X. Gao, Y. Dong, Z. Zhao, and H. Fu, "Development of high-silica fly ash-based adsorbents for efficient dye removal from wastewater: a comparative study of MSAM and SDS/FA," *RSC Adv*, vol. 15, no. 42, pp. 35158–35174, Oct. 2025, doi: 10.1039/D5RA05953D.
- [64] M. Tan *et al.*, "Fly ash-derived mesoporous silica with large pore volume for augmented CO₂ capture," *Fuel*, vol. 351, Nov. 2023, doi: 10.1016/j.fuel.2023.128874.
- [65] R. E. Nugraha *et al.*, "Jet-fuel range hydrocarbon production from Reutealis trisperma oil over Al-MCM-41 derived from Indonesian Kaolin with different Si/Al ratio," *Case Studies in Chemical and Environmental Engineering*, vol. 10, p. 100877, Dec. 2024, doi: 10.1016/J.CSCEE.2024.100877.
- [66] F. Yan *et al.*, "A green and facile synthesis of ordered mesoporous nanosilica using coal fly ash," *ACS Sustain Chem Eng*, vol. 4, no. 9, pp. 4654–4661, Sep. 2016, doi: 10.1021/acssuschemeng.6b00793.
- [67] K. J. D. Mackenzie *et al.*, "Fly Ash as a Secondary Raw Material Improving the Sustainable Characteristics of a Conventional Silicoaluminate Refractory Castable," *Inorganics* 2025, Vol. 13, Page 367, vol. 13, no. 11, p. 367, Nov. 2025, doi: 10.3390/INORGANICS13110367.
- [68] X. Zhao *et al.*, "Efficient separation and comprehensive extraction of aluminum, silicon, and iron from coal fly ash by a cascade extraction method," *J Clean Prod*, vol. 406, Jun. 2023, doi: 10.1016/j.jclepro.2023.137090.
- [69] R. K. Taggart, J. C. Hower, and H. Hsu-Kim, "Effects of roasting additives and leaching parameters on the extraction of rare earth elements from coal fly ash," *Int J Coal Geol*, vol. 196, pp. 106–114, Aug. 2018, doi: 10.1016/J.COAL.2018.06.021.
- [70] Y. Tian, S. Dai, and J. Wang, "Environmental standards and beneficial uses of waste-to-energy (WTE) residues in civil engineering applications," *Waste Disposal & Sustainable Energy* 2023 5:3, vol. 5, no. 3, pp. 323–350, Aug. 2023, doi: 10.1007/S42768-023-00140-8.