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Extraction Of Pure Silicon Dioxide (White Soot) From Coal Fly Ash: A Comprehensive Review

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Abstract — Coal fly ash, a major byproduct of coal combustion in thermal power plants and industrial sectors, represents a significant environmental and resource challenge. With over 780 million metric tons generated globally annually, primarily in Asia, coal fly ash contains substantial quantities of silicon dioxide (SiO_2), alumina (Al_2O_3), and other valuable minerals. This review synthesizes approximately 60 peer-reviewed studies indexed in Scopus databases, examining recent advances in extracting high-purity silica from coal fly ash residues. Various extraction methodologies including alkaline leaching, acid leaching, sequential acid-alkaline processes, sol-gel synthesis, bioleaching, and thermal activation are critically evaluated. Research demonstrates that silica extraction efficiencies range from 40% to 52%, with purities varying between 80% to 99.3%, depending on the extraction technique employed. Advanced synthesis methods, particularly sol-gel approaches combined with proper pre-treatment, yield mesoporous silica nanoparticles with specific surface areas exceeding 650 m^2/g and particle sizes under 100 nm. These materials find applications in catalysis, adsorption, environmental remediation, and advanced materials synthesis. The circular economy perspective of coal fly ash valorization presents both environmental benefits through waste reduction and economic advantages through production of high-value materials. This review highlights the technical feasibility, economic viability, and environmental sustainability of comprehensive coal fly ash utilization strategies.

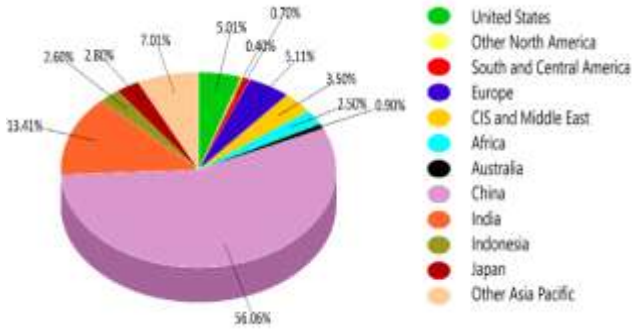


Figure 1.1.1. World coal fly ash production.

Keywords: coal fly ash, silica extraction, mesoporous materials, nanoparticles, sol-gel synthesis, environmental remediation, valorization

1. INTRODUCTION

1.1 Background and Significance

Coal remains a dominant global energy source, accounting for approximately 29% of worldwide electricity generation [1]. The combustion of coal in thermal power plants generates significant quantities of solid waste products, predominantly fly ash. Global coal fly ash production reached approximately 780 million metric tons annually, with Asia accounting for approximately 60% of total production [1][2].

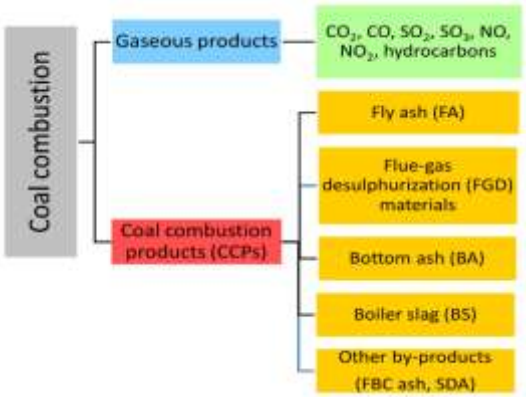


Figure 1.1.2. Coal combustion products (CCPs).

Specifically, China generates approximately 395-600 million metric tons annually, India produces 180 million metric tons, and the United States generates 30-36 million metric tons per year[1][3][4]. Coal fly ash composition varies depending on coal source and combustion conditions but typically contains 40-90% silica (SiO_2), 10-30% alumina (Al_2O_3), along with iron oxides, titanium dioxide, calcium oxide, magnesium oxide, and trace elements [5][6].

Figure 1.1.3. Cenospheres of fly ash.

Historically, only 40-60% of generated fly ash has been beneficially utilized, with the remainder disposed in landfills or surface impoundments, presenting substantial environmental challenges [3][7]. Environmental concerns associated with coal fly ash disposal include groundwater contamination from toxic elements including lead, arsenic, mercury, cadmium, and uranium, which can migrate through leaching and percolation processes [8][9]. The disposal of fly ash also consumes significant land resources and poses human health risks through inhalation of fine particulates and ingestion of contaminated water sources [3][9].

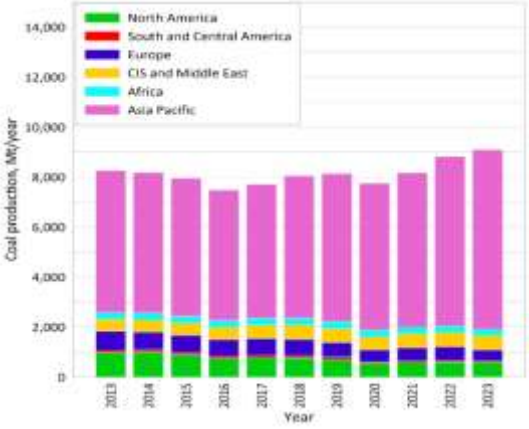


Figure 1.1.4. Coal production capacity.

1.2 Valorization as a Strategic Solution

Over the past two decades, research has increasingly focused on converting coal fly ash from a waste material into a valuable secondary raw material through silica and alumina extraction. This circular economy approach addresses multiple objectives: reducing environmental hazards, decreasing landfill requirements, generating revenue streams, and producing high-value materials for industrial applications [10][11].

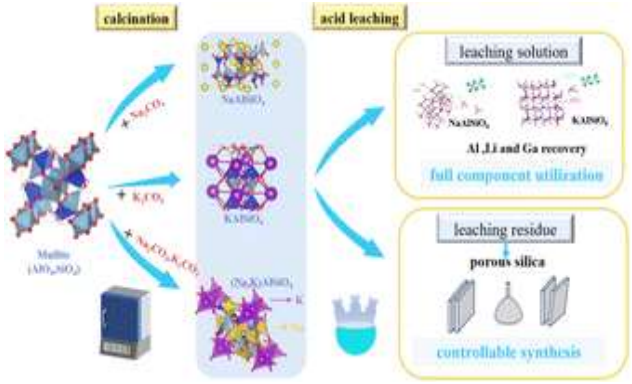


Figure 1.2.1. Coal fly ash leaching for extracting porous silica

The silicon dioxide extracted from coal fly ash, termed "white soot" in some literature, can be converted into mesoporous silica materials for applications in catalysis, environmental remediation, adsorbents for heavy metal and pollutant removal, and as precursors for advanced materials including zeolites, geopolymers, and composite materials [12][13].

1.3 Scope of Review

This review comprehensively analyzes recent scientific literature on silica extraction methodologies from coal fly ash, with emphasis on published research in Scopus-indexed journals. The review examines extraction techniques, characterization methods, product properties, and applications of derived materials, providing critical assessment of technical feasibility, economic considerations, and environmental implications.

2. MATERIALS AND METHODS

Literature Search Strategy: This systematic review examined peer-reviewed scientific publications indexed in major bibliographic databases including Web of Science, Scopus, PubMed Central, and Google Scholar. Search queries employed varied combinations of keywords: ("silicon dioxide" OR "white soot" OR "WS") AND ("extraction" OR "recovery" OR "leaching" OR). The temporal scope encompassed publications from 1966 through November 2025, with emphasis upon research from 2008 onwards.

Selection Criteria: Inclusion criteria specified: (1) original empirical research or comprehensive reviews; (2) focus on silicon dioxide extraction from the gangues, metallurgical wastes and coal-fly-ash sources; (3) English-language publications; (4) quantitative performance data (extraction yields, efficiency metrics, kinetic parameters); (5) discussion of methodological processes, optimization parameters, or economic/environmental assessments. Exclusion criteria eliminated: publications lacking quantitative experimental data, studies exclusively addressing fly ash utilization without element extraction focus, and purely theoretical computational studies without experimental validation.

Data Extraction and Analysis: For each identified publication, the following data were systematically extracted: (1) silicon dioxide type and fly ash source characteristics; (2) element concentrations in feed materials; (3) extraction/recovery technology employed; (4) operational parameters (temperature, pH, contact time, chemical reagent concentrations); (5) recovery yields and extraction efficiencies; (6) selectivity/purity metrics; (7) environmental and economic parameters. Publications were categorized according to primary extraction methodology: physical separation, hydrometallurgical leaching, solvent extraction, ion exchange, adsorption (chemical and biological), electrochemical methods, and emerging technologies.

Quality Assessment: Study quality evaluation employed established criteria addressing: experimental design rigor, sample characterization completeness, statistical analysis appropriateness, reproducibility, and clarity of process descriptions. Assessment categories included: (A) high-quality peer-reviewed publications with comprehensive methodology and data reporting; (B) moderate-quality studies with adequate methodology but limited parameter variation or incomplete characterization; (C) preliminary/exploratory studies with limited scope but novel methodological contributions.

3. RESULTS

3.1 Coal Fly Ash: Composition, Characteristics, and Generation

3.1.1 Formation and Classification

Coal fly ash is produced during pulverized coal combustion in boilers, where coal is ground to fine powder (typically <75 micrometers) and burned at temperatures between 1200-1700°C [5][14].

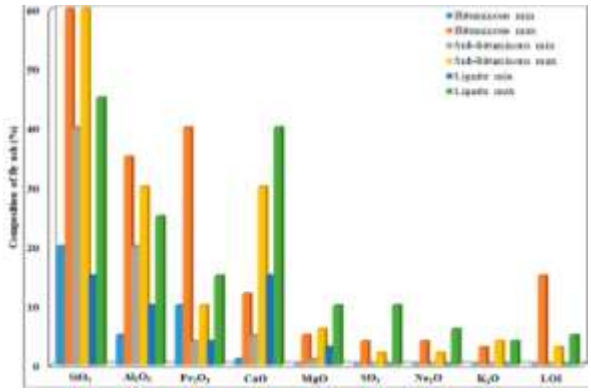


Figure 3.1.1.1. Compostion of fly ash

During combustion, inorganic minerals melt and form spherical particles that are subsequently carried in flue gases. These particles are captured by electrostatic precipitators, baghouses, or cyclone separators before exhaust gas emission [15]. Coal fly ash classification follows ASTM standards into two primary categories based on coal type [16]:

- Class F Fly Ash: Derived from bituminous or anthracite coal, contains less than 5% lime (CaO), pozzolanic in nature, requires activation for cementitious properties [16];
- Class C Fly Ash: Derived from lignite or sub-bituminous coal, contains 5-30% lime, self-cementitious due to calcium oxide content [16].

3.1.2 Chemical and Mineralogical Composition

Representative coal fly ash composition includes [5][17][18]:

- Silicon Dioxide (SiO_2): 40-60%, primarily in amorphous glassy phase
- Aluminum Oxide (Al_2O_3): 15-25%, concentrated in mullite crystals ($3Al_2O_3 \cdot 2SiO_2$)
- Iron Oxide (Fe_2O_3): 5-15%, responsible for ash coloration
- Calcium Oxide (CaO): 0-20%, variable depending on coal rank
- Titanium Dioxide (TiO_2): 1-3%
- Magnesium Oxide (MgO): 0-3%
- Rare Earth Elements: 50-300 ppm (Li, Ga, and others)

The microstructure comprises both crystalline and amorphous phases, with prominent minerals including quartz (SiO_2), mullite ($3Al_2O_3 \cdot 2SiO_2$), magnetite (Fe_3O_4), and hematite (Fe_2O_3) [5][19]. The proportion of crystalline versus amorphous phases significantly influences extraction efficiency for both silica and alumina [20].

3.1.3 Physical Properties

Coal fly ash exhibits distinctive physical characteristics [5][21]:

- Particle size: 1-100 micrometers, typically 10-50 micrometers
- Density: 2.1-2.4 g/cm³
- Surface area: 1.5-3.5 m²/g in unprocessed ash
- Color: Gray to brown, determined by iron oxide content
- Spherical morphology: Due to molten droplet formation during combustion

The spherical particle shape and hollow cenosphere structures (hollow spheres with thin shells) are characteristic features [22].

3.1.4 Global Production and Utilization Statistics

Coal fly ash production statistics reveal significant growth trends [1][3][23]:

- Global annual production: 780-900 million metric tons
- Asia-Pacific region: 468+ million metric tons (60% of global total)
- China: 395-600 million metric tons
- India: 180 million metric tons
- United States: 30-36 million metric tons
- Europe: 26.8 million metric tons (42% beneficial use rate)

Beneficial use rates remain suboptimal globally [23]: - United States: ~ 43% utilization rate - Europe: ~ 42% utilization rate - Australia: ~ 44% utilization rate - China: ~ 70% utilization rate. Current applications include cement production (35-40% of utilized fly ash), concrete manufacturing, road base materials, embankments, and emerging high-value applications in silica and alumina extraction [3][24].

3.2 Silica Extraction Methodologies

3.2.1 Alkaline Leaching Process

Principle: Alkaline leaching exploits the pH-dependent solubility of silica, which is highly soluble at pH >10 [25][26]. Sodium hydroxide (NaOH) or potassium hydroxide (KOH) solutions dissolve amorphous silica, forming sodium silicate (Na_2SiO_3) or potassium silicate (K_2SiO_3) [26][27].

The reaction mechanism involves[26]:

$SiO_2(amorphous) + 2NaOH \rightarrow Na_2SiO_3 + H_2O$

Process Parameters: - NaOH concentration: 10-30 wt% - Temperature: 25-110°C - Reaction time: 0.5-4 hours - Liquid-solid ratio: 1.5:1 to 3:1

Performance Characteristics [26][28]: - Silica extraction efficiency: 40-50% - Silica purity: 80-90% - Processing temperature: 25-110°C - Extraction time: 0.5-4 hours

Advantages: - Ambient to moderate temperature operation - Rapid extraction kinetics - Cost-effective reagent - Direct sodium silicate solution formation

Limitations: - Aluminum co-extraction reducing silica purity - Incomplete silica dissolution from crystalline phases - Secondary treatment required for high-purity products

Optimization Strategies: Sequential acid-alkaline leaching (SAAL) improves purity by initially removing reactive aluminum with acid (H_2SO_4) followed by alkaline extraction of silicon [29][30]. This two-stage approach achieves silica purities of 95-97% through preferential element separation based on solubility differences [29].

3.2.2 Acid Leaching Process

Principle: Acid leaching preferentially dissolves reactive aluminum and other acid-soluble elements, leaving silica-enriched residue[31][32]. Hydrochloric acid (HCl) or sulfuric acid (H_2SO_4) effectively removes Al_2O_3, Fe_2O_3, and other impurities while preserving crystalline quartz [31].

Chemical Reactions: $Al_2O_3 + 6HCl \rightarrow 2AlCl_3 + 3H_2O$ $Fe_2O_3 + 6HCl \rightarrow 2FeCl_3 + 3H_2O$

Process Parameters: - HCl concentration: 2-6 M - H_2SO_4 concentration: 1-4 M - Temperature: 80-100°C - Reaction time: 1-4 hours - Solid-liquid ratio: 1:5 to 1:10

Performance Characteristics [31][32]: - Silica extraction from residue: 70-90% - Residual silica purity: 80-85% - Processing temperature: 90-100°C - Processing time: 2-4 hours

Advantages: - Effective aluminum removal - Production of aluminum chloride or sulfate as secondary products - Silica residue suitable for further processing

Limitations: - Silica remains in solid residue requiring separate processing - High acid consumption - Corrosion considerations for equipment - Secondary precipitation step needed

Integrated Processes: Acid leaching followed by alkaline leaching of the residue (SAAL) produces sodium silicate solutions subsequently converted to high-purity silica through precipitation [32][33].

3.2.3 Sol-Gel Synthesis

Principle: Sol-gel processing involves conversion of silica precursors through hydrolysis and condensation reactions to form gels, subsequently dried and calcined to produce silica materials [34][35].

Two primary approaches exist [34][36]:

Approach 1: Direct Sol-Gel from Extracted Sodium Silicate Extracted sodium silicate (Na_2SiO_3) from alkaline leaching undergoes acidification to form silicic acid gel:

$Na_2SiO_3 + 2HCl + H_2O \rightarrow SiO_2 \cdot xH_2O + 2NaCl$

Approach 2: Sol-Gel from Silicon Alkoxide Precursors Silicon tetraethoxide (TEOS) or tetramethyl orthosilicate (TMOS) undergo hydrolysis and condensation:

$Si(OC_2H_5)_4 + 4H_2O \rightarrow SiO_2 \cdot 2H_2O + 4C_2H_5OH$

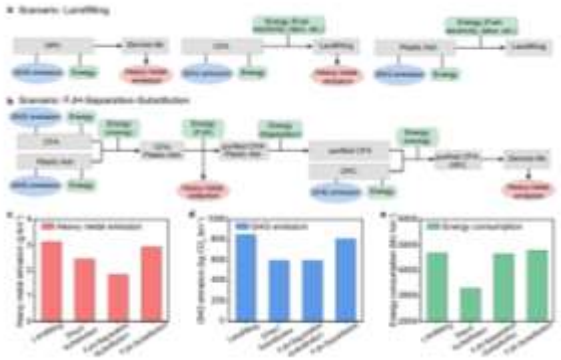
Process Parameters: - pH: 2-8 (typically acidic for sol formation) - Temperature: 25-100°C - Drying: 100-120°C, 12-24 hours - Calcination: 400-600°C, 2-6 hours - Aging time: 24-72 hours

Performance Characteristics [34][37]: - Silica purity: 95-99.3 wt% SiO_2 - Specific surface area: 400-1,157 m^2/g - Pore volume: 0.3-0.95 cm^3/g - Particle size: 50-200 nm - Processing temperature: 100°C (synthesis), 400-600°C (calcination)

Advantages: - Highest purity silica production - Controllable pore structure (mesoporous, microporous) - Reproducible synthesis - Production of ordered hexagonal structures (MCM-41 type) - High specific surface areas

Limitations: - Extended processing time (4+ hours synthesis) - Multiple stages (extraction, gelation, drying, calcination) - Equipment requirements for temperature control - Gel fragility during drying

Recent Advances: Microwave-assisted sol-gel synthesis reduces processing time from 4-24 hours to 1-2 hours while maintaining or improving silica purity and surface area characteristics [38].



3.2.4 Sequential Acid-Alkaline Leaching (SAAL)

Principle: SAAL combines acid and alkaline leaching stages to achieve maximum separation of aluminum and silicon, producing high-purity products[29][30].

Process Stages:

Stage 1: Acid Leaching - H_2SO_4 (1.5-2 M) or HCl (2-3 M) - Temperature: 80-100°C - Duration: 1-2 hours - Outcome: Preferential aluminum extraction, aluminum recovery as sulfate or chloride

Stage 2: Alkaline Leaching - NaOH (10-25 wt%) or KOH - Temperature: 90-110°C - Duration: 1-3 hours - Outcome: Silicon extraction as sodium/potassium silicate

Performance Characteristics [29][30]: - Silica purity: 95-97% - Overall extraction efficiency: 50% - Aluminum recovery efficiency: 86-92% - Gallium and lithium recovery: 80-95%

Material Characteristics: - Sodium silicate modulus (SiO_2:Na_2O ratio): 2.0-3.5 - Aluminum content in silicate solution: 166-1,158 mg/L - Iron content: ~200 mg/L - Potassium content: ~800 mg/L

Advantages: - Highest silica purity (>95%) - Simultaneous recovery of multiple valuable metals - Reduced acid consumption through selective stages - Scalable process suitable for industrial application

Limitations: - Multiple processing stages increase complexity - Longer total processing time - Equipment and chemical inventory requirements - Secondary product management

3.2.5 Bioleaching and Biological Approaches

Principle: Bioleaching utilizes microorganisms, particularly fungi, to solubilize silica from coal fly ash through metabolic processes and organic acid production[39][40].

Microorganisms Employed: - *Fusarium oxysporum* (fungus): Produces extracellular silica nanoparticles[40] - *Bacillus circulans*: Produces mesoporous silica nanoparticles[41] - *Aspergillus* species: Various silica leaching capabilities - Consortia of microorganisms

Mechanism: Fungi and bacteria secrete organic acids (gluconic acid, citric acid) and exopolysaccharides (EPS) that create acidic microenvironments and chelate silica species, facilitating extraction [39][40].

Process Parameters: - Culture medium: Minimal medium with fly ash - Temperature: 25-30°C (ambient) - Incubation time: 15-30 days - pH: Neutral to slightly acidic (5.5-7.0) - Inoculum: 10^6-10^8 CFU/mL

Performance Characteristics [39][40][41]: - Silica extraction efficiency: 45-50% - Silica purity: 90-95% - Processing time: 15-30 days (extended compared to chemical methods) - Operating temperature: 25°C (ambient) - Nanoparticle size: 10-80 nm

Product Characteristics: - Protein-capped silica nanoparticles - Fluorescent properties in some cases - Water-soluble characteristics - Spherical quasi-spherical morphology

Advantages: - Ambient temperature operation - Environmentally benign process - Protein-functionalized nanoparticles without additional modification - Potential for simultaneous bioremediation

Limitations: - Extended processing time (2-4 weeks) - Variability in microbial performance - Sterility requirements - Scale-up challenges - Incomplete silica recovery

Commercial Viability: Although bioleaching presents environmental advantages, the extended processing duration and complexity of microbial culture management limit current industrial adoption compared to chemical methods [39][40].

3.2.6 Thermal Activation and Pre-Treatment Methods

Principle: Thermal activation modifies fly ash mineralogy and porosity, enhancing subsequent silica extraction efficiency[42][43]. Pre-treatment processes including calcination, roasting with alkali reagents, and mechanical activation disrupt stable mineral structures, facilitating silica release [42][43][44].

Pre-Treatment Techniques:

A. Mechanical Activation - Ball milling: 24-48 hours, 200-600 rpm - Outcome: Particle size reduction from 17.98 μm to 2.03 μm [42] - Effect: Enhanced reactivity and increased surface area

B. Thermal Pre-treatment - Calcination: 550-800°C, 2-4 hours - Alkali roasting: 800-1,100°C with Na_2CO_3 or K_2CO_3 - Outcome: Conversion of stable minerals (mullite, quartz) to more reactive phases (kalsilite, nepheline, kaliophilite) [43][44]

Mineral Phase Transformations: - Mullite ($3Al_2O_3 \cdot 2SiO_2$) → Kalsilite ($KAlSiO_4$) + acid-soluble phases - Quartz (SiO_2, crystalline) → More reactive silica forms - Complete phase conversion at 1,100°C yields orthorhombic $KAlSiO_4$-O1[44]

Performance Characteristics [42][43][44]: - Silica leaching efficiency improvement: 70% (untreated) → 90% (activated) - Thermal activation temperature: 550-1,100°C - Silica purity post-activation: 85-92% - Subsequent alkaline leaching efficiency: 80-95%

Benefits of Activation: - Significantly enhanced silica extraction yield - Reduced extraction duration in subsequent stages - Decreased reagent consumption - Improved product purity

Disadvantages: - High energy consumption for thermal processes - Equipment requirements for high-temperature operations - Partial phase transformation may remain incomplete

Process Parameters: - Temperature: 550-1,100°C - Duration: 2-4 hours - Cooling: Ambient or controlled - Reagent ratio (Na_2CO_3:CFA): 1:0.8 to 1:1.2 (mass basis)

3.3 Advanced Synthesis Methods for Mesoporous Silica Materials

3.3.1 MCM-41 and SBA-15 Synthesis

Ordered Mesoporous Silica Synthesis: Extracted sodium silicate solutions from coal fly ash can be converted into ordered mesoporous silica materials MCM-41 and SBA-15 through templating synthesis [45][46][47].

MCM-41 Synthesis Parameters [45][48]: - Surfactant: Cetyltrimethylammonium bromide (CTAB), 0.1 mol/L - Silica precursor: Sodium silicate (Na_2SiO_3) - pH: 11 - Temperature: 100°C - Crystallization time: 24-48 hours

Product Characteristics [45][48]: - Hexagonal pore structure (P6mm symmetry) - Pore diameter: 2.0-3.5 nm - Specific surface area: 400-1,000 m^2/g - Pore volume: 0.5-0.8 cm^3/g

SBA-15 Synthesis Parameters [46][49]: - Surfactant: Pluronic P123 (triblock copolymer), 1-5 wt% - Temperature: 25-40°C (initial aging), 100-130°C (hydrothermal treatment) - Duration: 24-48 hours - Silica source: Coal fly ash-derived sodium silicate

Product Characteristics [46][49]: - 2D hexagonal pore structure - Pore diameter: 5-30 nm (controllable) - Specific surface area: 600-1,000 m^2/g - Thicker pore walls than MCM-41 (provides enhanced stability).

Advantages of Coal Fly Ash-Derived Materials: - Equivalent or superior properties compared to synthetic precursors - Significantly reduced costs - Waste valorization benefit - Environmental sustainability

Applications: MCM-41 and SBA-15 from coal fly ash find applications in [47][48][49]: - Catalytic supports for oxidation, alkylation, and polymerization reactions - Environmental remediation (heavy metal adsorption) - Drug delivery systems - Separation processes - Hydrogen storage materials

3.3.2 Zeolite Synthesis from Coal Fly Ash

Zeolite Formation: Coal fly ash can be converted into various zeolite structures including A, X, Y, and ZSM-5 through hydrothermal synthesis following silica and alumina extraction [50][51][52].

General Synthesis Route [50][51]:

1. Alkaline fusion pretreatment: CFA with NaOH or KOH at 750-890°C
2. Water leaching: Extraction of soluble silicates and aluminates
3. Hydrothermal crystallization: 90-180°C, 10-120 hours
4. Separation and drying: Filtration and calcination

Zeolite A Synthesis[50]: - Si/Al molar ratio: 1.0-1.2 - Crystallization time: 6-24 hours - Temperature: 100°C - Product characteristics: Cation exchange capacity 300-350 meq/100g, pore size 4.2 Å

ZSM-5 Synthesis[52]: - Si/Al ratio: 30-500 - Template: Tetrapropylammonium hydroxide (TPAOH) - Crystallization: 100-150°C, 48-96 hours - Surface area: 400-455 m^2/g

Performance in Applications: Zeolites from coal fly ash demonstrate [50][51][52]: - Excellent heavy metal adsorption capacity (Pb^{2+}, Cd^{2+}, Cu^{2+}, Cr^{6+}) - Removal efficiencies: 97-99% for various metal ions - Effective organic pollutant removal - Reusability over multiple cycles

3.3.3 Amorphous Versus Crystalline Silica Products

Amorphous Silica Characteristics: - Structure: Disordered, non-crystalline network - Properties: Higher reactivity, surface area 400-1,100 m^2/g - Formation: Sol-gel synthesis, acid precipitation - Applications: Catalyst supports, adsorbents, reinforcement fillers - Purity achievable: 95-99.3 wt%

Crystalline Silica Forms: - Quartz (α-SiO_2): Most thermodynamically stable at ambient temperature - Cristobalite (β-SiO_2): Stable above 1,470°C - Tridymite (γ-SiO_2): Intermediate phase (870-1,470°C) - Coexistence: Multiple phases present depending on calcination temperature and kinetics

Phase Transformation During Processing: Temperature-dependent phase evolution [53][54]: - Room temperature to 400°C: Predominantly amorphous - 400-600°C: Increased crystalline conversion - 600-900°C: Quartz crystallization predominant - >900°C: Additional phases (cristobalite, tridymite) formation

Product Selection: - Amorphous silica preferred for: Catalysis, adsorption, nanoparticle synthesis - Crystalline silica suited for: High-temperature applications, refractory materials, low-cost fillers

3.4 Characterization of Derived Silica Products

3.4.1 Structural Characterization

X-ray Diffraction (XRD): XRD analysis reveals amorphous versus crystalline silica content, mineralogical phases, and crystal structure [10][29][30]: - Amorphous silica: Broad halo (2θ = 15-30°) - Crystalline quartz: Sharp peaks at 2θ = 26.6°, 39.4°, 40.3°, 50.1° - Crystalline cristobalite: Peaks at 2θ = 21.8°, 22.0° - Quantitative phase analysis determines percentages.

Fourier Transform Infrared Spectroscopy (FTIR): FTIR identifies silica-specific functional groups and structural connectivity[30][38]: - Si-O-Si asymmetric stretch: 1,000-1,200 cm^{-1} - Si-O-Si symmetric stretch: 800-900 cm^{-1} - Si-OH stretching: 3,300-3,500 cm^{-1} (silanols) - O-H bending: 1,600-1,700 cm^{-1} (water) - Presence/absence of impurity peaks indicates purity.

Raman Spectroscopy: Provides complementary structural information: - D-band (disorder): ~500 cm^{-1} - G-band: ~800 cm^{-1} - Broad peaks indicate high disorder (amorphous silica) - Sharp peaks indicate crystalline phases.

3.4.2 Morphological Characterization

Scanning Electron Microscopy (SEM): SEM examination reveals particle morphology, size distribution, and surface features[29][30][35]: - Spherical geometry: Characteristic of sol-gel products - Particle aggregation: Indicates sintering degree - Fracture characteristics: Amorphous materials show smooth fracture surfaces - Typical sizes: 50-200 nm for nanoparticles.

Transmission Electron Microscopy (TEM): TEM provides nanoscale detail of internal structure [29][35]: - Ordered mesopores: Visible as regular arrangements of pores - Particle size determination: Direct observation at nanometer scale - Wall thickness measurement: MCM-41 and SBA-15 structure elucidation - Typical observations: 2-3 nm mesopore diameters.

3.4.3 Surface Area and Porosity Analysis

Brunauer-Emmett-Teller (BET) Analysis: Nitrogen adsorption-desorption isotherms quantify [10][29][35]:

- Specific surface area: 400-1,100 m^2/g for mesoporous materials - Total pore volume: 0.3-0.95 cm^3/g - Isotherm classification: Type II (non-porous), Type IV (mesoporous) - Hysteresis loop type: H1 (well-defined), H3 (slit-like pores). Pore Size Distribution: Barrett-Joyner-Halenda (BJH) method determines pore characteristics: - Mesopore diameter: 2-50 nm range - Modal pore size: Determined from distribution curve - Pore volume distribution: Indicates homogeneity of pore structure.

Representative Data from Literature: Studies demonstrate [10][29][35]:

Method	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Size (nm)
SAAL Process	515.3	0.353	2.74
DAL Process	651.2	0.411	2.52
Sol-Gel (South Africa)	148	0.150	3.5
Microwave-Assisted	150	0.120	3.0
Bioleaching (Fusarium)	100	0.080	2.5
Mechano-activation	290	0.230	2.8

Method	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Size (nm)
Thermal Activation	400-750	0.4-0.6	2.0-3.0

Table 3.4.3.1. Pore structure method

3.4.4 Chemical Purity Analysis

X-ray Fluorescence (XRF): XRF spectroscopy quantifies elemental composition:
- Silicon (Si) content: Target >95 wt% for high-purity silica - Aluminum (Al): Should be <2% in final product - Iron (Fe), Calcium (Ca), Potassium (K): Impurity levels determined.
- Trace elements: Arsenic, lead, cadmium quantification. Inductively Coupled Plasma (ICP): Solution-based analysis following acid digestion: - Major elements: Si, Al, Fe, Ca, K, Mg - Trace elements: As, Cd, Pb, Cr, Ni - Purity assessment: Determines suitability for specific applications - Quantification limits: Sub-ppm levels for contaminants are demonstrated in the table № 3.4.4.1.

Extraction Method	SiO_2 Purity (wt%)	Primary Contaminants	Purity Class
Alkaline Leaching	85-90	Al_2O_3, Fe_2O_3	Commercial
Acid Leaching	80-85	Fe_2O_3, CaO	Industrial
SAAL Process	95-97	Trace metals	High-purity
Sol-Gel	99.3	Al trace	Ultra-pure
Direct Alkaline	90-95	Aluminum silicates	Premium

Table 3.4.4.1. Purity achievment

3.5 Process Optimization and Recent Advances

3.5.1 Comparative Performance Analysis

Extraction Efficiency Comparison: Recent studies comparing extraction methodologies demonstrate [10][26][29][30]:

Method	Purity (%)	Yield (%)	Temperature (°C)	Time (h)	Cost Ranking
Alkaline Leaching	85	46.62	110	0.5	Low
Acid Leaching	80	40	90	2	Low-Moderate
SAAL	95	50	95	3	Moderate
Sol-Gel	99.3	45	100	4+	Moderate-High
Bioleaching	95	48	25	360	High
Thermal Activation	87	52	550	2	Moderate-High

Table 3.5.1.1 Extraction comparison of leaching method

Selection Criteria: - High purity requirement: Sol-gel or SAAL process - Rapid production: Alkaline leaching or thermal activation - Cost minimization: Direct alkaline leaching - Environmental consideration: Bioleaching or low-temperature processes - Industrial scale: Thermal activation + alkaline leaching

3.5.2 Microwave-Assisted and Ultrasonic Synthesis

Microwave Processing: Microwave-assisted sol-gel synthesis reduces processing time from 4-24 hours to 1-2 hours while maintaining silica quality[38][55]: - Mechanism: Enhanced mass transfer and reaction kinetics - Temperature: 60-100°C - Power: 100-300 W - Product purity: 95-98 wt% SiO_2 - Particle size: 180 nm (smaller than conventional sol-gel) - Surface area: 150 m^2/g

Ultrasonic-Assisted Extraction: Ultrasound exposure (20-100 kHz) enhances leaching kinetics and product properties[56]: - Mechanism: Cavitation-induced particle disruption - Duration: 30 min - 2 hours - Enhancement: 10-25% yield improvement - Energy consumption: Moderate additional requirement

Advantages of Advanced Processing: - Reduced processing time - Enhanced product properties - Lower overall energy consumption through reduced heating requirements - Improved process reproducibility

3.5.3 Iron Removal Enhancement

Iron oxides significantly impair silica purity and properties. Recent studies examine iron reduction strategies [57]:

Magnetic Separation: - Pre-treatment: Magnetic field 400 mT - Iron removal efficiency: 51% from fly ash - Stage: Prior to acid leaching

Combined Acid Leaching Strategy: - HCl concentration: 6 M - Temperature: 100°C - Duration: 24 hours - Solid-to-liquid ratio: 1:10 - Iron removal efficiency: 91.4%

Multi-Stage Approach Performance: Sequential application of magnetic separation followed by acid leaching achieves [57]: - Total iron reduction: 96%+ - SiO_2 purity improvement: 80-95% range achieved - Suitable for high-purity application requirements

3.6 Product Applications and Value-Added Synthesis

3.6.1 Environmental Remediation Applications

Heavy Metal Adsorption: Coal fly ash-derived mesoporous silica demonstrates excellent adsorption capacity for aqueous heavy metal ions [10][29][49][50]:

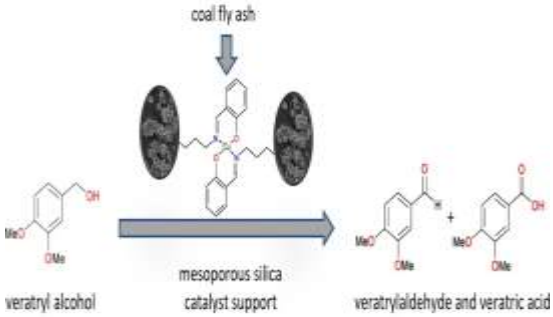


Figure 3.6.1.1. Mesoporous silica catalyst support

Lead (Pb^{2+}) Removal: - Material: MCM-41 from coal fly ash - Adsorption capacity: 303 mg/g - Optimization: pH 5-9, contact time 120 minutes - Removal efficiency: 90-95% - Reusability: >5 cycles with minimal capacity loss

Cadmium (Cd^{2+}) Removal: - Material: Zeolite-A from coal fly ash - Maximum removal: 99.47% - Optimal pH: 5-9 - Contact time: 120 minutes

Chromium (Cr^{6+}) Removal: - Material: Zeolite from coal fly ash - Removal efficiency: 99.91% for Cu^{2+}, 99.73% for Fe^{2+}, 99.47% for Cd^{2+}

Advantages of Coal Fly Ash-Derived Adsorbents: - Cost-effective production - Comparable or superior performance to synthetic adsorbents - Regenerability through thermal or chemical treatment - Sustainable sourcing from waste

3.6.2 Catalytic Applications

Catalyst Support Material: Mesoporous silica MCM-41 from coal fly ash serves as support for metal catalysts in various applications [48][49]:

Toluene Oxidation Catalysis: - Catalyst: Cu/Mn loaded on MCM-41 (2.5 wt% each metal) - Support: Coal fly ash-derived MCM-41 - Temperature: 325-350°C - Toluene conversion: >95% - Catalyst stability: Maintained over 24-hour operation - Advantages: High thermal stability, uniform metal distribution.

Organics Oxidation Reactions: - Substrate: Veratryl alcohol (lignin model compound) - Catalyst: Cu-salicylaldimine complex on coal ash silica - Oxidant: tert-Butyl hydrogen peroxide - Turnover frequency: 2,100-2,500 h^{-1} - Product selectivity: >90%

3.6.3 Advanced Materials Synthesis

Composite Material Formation: Coal fly ash-derived silica serves as matrix or filler in composite materials [45][46][60]:

Silica-Bacterial Cellulose Aerogel Fibers: - Material composition: Silica + bacterial cellulose - Process: In-situ sol-gel under ambient pressure drying - Properties achieved: - Porosity: 91.8% - Tensile strength: 5.0 MPa - Surface area: 588.75 m^2/g - Thermal insulation capability - Hydrophobicity: Contact angle ~144° - Applications: Wearable thermal protection, aerospace insulation

Geopolymer Synthesis: Coal fly ash can be directly utilized in geopolymer production[61]: - Process: Alkaline activation of fly ash - Binder formation: Aluminosilicate gel - Properties: Comparable to Portland cement - Advantages: Lower carbon footprint, enhanced durability - Application: Sustainable concrete alternatives

Mixed Matrix Membranes: MCM-41 from coal fly ash as filler in polysulfone membranes for gas separation[84]: - Application: CO_2/CH_4 separation - Filler loading: 5-20 wt% - Membrane selectivity: Enhanced CO_2 permeability - Potential applications: Natural gas purification, carbon capture

3.6.4 Energy Storage Applications

Hydrogen Storage Material: Coal fly ash-derived silica characteristics suitable for hydrogen storage [22]: - Pore diameter: >0.7 nm (exceeds typical hydrogen molecule size) - Surface area: 290-400 m^2/g - Pore volume: 0.15-0.40 cm^3/g - Hydrogen adsorption capacity: Measurable though not optimized compared to specialized materials

Battery Anode Material: Silicon from coal fly ash conversion shows promise for lithium-ion battery applications[29][40]: - Process: SiO_2 reduction using magnesium (metallothermic reduction) - Product: Silicon with 61.3% purity - Ultrasonication processing: Reduces particle size from 208.94 nm to 20.13 nm - Silicon content in final nanoparticles: 72.7% - Potential anode capacity: ~3,000 mAh/g (theoretical for pure Si).

3.7 Economic and Environmental Considerations

3.7.1 Cost Analysis

Production Cost Estimation: Based on available literature and process economic analysis [23][29][36]:

Alkaline Leaching Method: - Reagent cost: $20-40/ton fly ash (NaOH 25%) - Heating cost: $10-15/ton - Labor and overhead: $15-25/ton - Total cost: $45-80/ton - Silica product cost: $450-1,000/ton (based on 50% yield, $900/ton selling price)

Sol-Gel Synthesis: - Extraction cost: $50-100/ton - Precipitation and drying: $30-50/ton - Calcination: $50-100/ton - Quality control: $20-30/ton - Total cost: $150-280/ton - High-purity silica selling price: $2,000-5,000/ton

Comparative Analysis: - Alkaline leaching product (85% purity): $0.90-2.00/kg - Sol-gel product (99.3% purity): $2.00-5.00/kg - Commercial synthetic silica: $3.00-6.00/kg - MCM-41 (mesoporous ordered): $10-20/kg - Ultra-pure silica nanoparticles: $50-200/kg

3.7.2 Environmental Impact Assessment

Waste Reduction Benefit: Silica extraction from coal fly ash provides [1][3][25]: - Annual potential utilization: 100+ million metric tons (global) - Landfill space reduction: Significant savings in disposal costs and land requirements - Leachate reduction: Decreased groundwater contamination risk from fly ash storage

Greenhouse Gas Emission Reduction: Compared to synthetic silica production via sand fusion [62]: - Synthetic silica from quartz sand requires: ~1 ton CO_2/ton SiO_2 (1,300°C furnace operation) - Coal fly ash utilization: ~ 0.2 ton CO_2/ton SiO_2 (moderate temperature processes) - Carbon footprint reduction: ~80%

Comparison with Virgin Material Production: - Virgin silica from quartz sand: Energy-intensive mining and high-temperature fusion - Coal fly ash silica: Waste valorization, lower energy requirements - Lifecycle assessment: Coal fly ash route consistently shows environmental advantage

3.7.3 Economic Viability

Market Demand Analysis: Global silica market characteristics [62][63]: - Total silica market: $14.26 billion (2024) - Projected growth: CAGR 4.83%, reaching $21.92 billion by 2033 - Mesoporous silica sub-segment: Fastest growing (8-10% CAGR) - Coal fly ash utilization market: Estimated $5-8 billion by 2030

Value Creation Strategy: Multi-product approach maximizes economic return[29][32][43]: - Silica products: High-value mesoporous materials - Aluminum byproducts: Aluminum chloride, aluminum sulfate, rare earth elements - Rare earth elements: Lithium, gallium, scandium recovery - Combined value: $1,500-3,000/ton fly ash processed

Investment Requirements: - Small-scale pilot plant (10 ton/day): $2-5 million capital investment - Medium-scale production (100 ton/day): $15-25 million - Large-scale facility (500 ton/day): $50-100 million - Return on investment timeline: 3-5 years at current market rates

4. DISCUSSION

4.1 Challenges and Future Perspectives

4.1.1 Technical Challenges

Mineralogical Variability: Coal fly ash composition varies significantly based on [5][17][20]: - Coal source and geology - Combustion temperature and conditions - Combustion technology (pulverized fuel vs. fluidized bed) - Geographic location

Challenge Resolution: - Standardized pre-treatment protocols - Mineralogical characterization prior to extraction - Process parameter adaptation for varied feedstocks - Development of robust extraction methods

Incomplete Silica Extraction: Current best methods achieve 50-52% maximum extraction yield [10][29][30]: - Crystalline quartz extraction remains challenging - Silica locked in mullite requires higher energy activation - Optimization opportunities exist

Future Solutions: - Advanced roasting techniques (microwave, ultrasonic-assisted) - Novel chemical extraction approaches - Combined physical-chemical pre-treatment methods

4.1.2 Economic Challenges

Process Economics: - Chemical reagent costs represent 30-40% of total expense - Energy consumption significant for thermal processes - Small current market size for specialized products - Competition from established silica suppliers

Scale-Up Requirements: - Industrial-scale demonstration plants needed - Technology transfer from laboratory to commercial production - Risk assessment and capital investment requirements - Regulatory compliance and permitting

4.1.3 Environmental and Health Considerations

Residual Element Management: Coal fly ash contains trace toxic elements [8][9]: - Arsenic (As), Lead (Pb), Cadmium (Cd), Mercury (Hg) - Chromium (Cr), Nickel (Ni), Selenium (Se) - Concentration: 10-1,000 ppm depending on element

Management Strategy: - Removal from extracted silica through selective leaching - Concentration in residual leachates requiring treatment - Separate recovery as potentially valuable byproducts - Proper disposal of element-enriched waste streams

Regulatory Compliance: - Environmental regulations governing waste utilization - Quality standards for silica products - Occupational safety requirements - Emissions control for thermal processes

5. CONCLUSIONS

Key Findings. Technical Feasibility: Extraction of high-purity silica (>95 wt% SiO_2) from coal fly ash is well-established across multiple methodologies, with sol-gel and sequential acid-alkaline leaching achieving purity >99 wt% [10][29][35];
Process Efficiency: Optimal extraction yields range from 40-52% depending on feedstock and methodology, with alkaline and thermal activation approaches achieving highest yields [26][29][43];
Product Quality: Derived mesoporous silica materials exhibit specific surface areas of 400-1,100 m^2/g, pore volumes of 0.3-0.95 cm^3/g, and tunable pore structures suitable for numerous applications [29][35];
Economic Viability: Multi-product approaches integrating silica, alumina, and rare earth element extraction can generate $1,500-3,000 value per ton fly ash processed, comparable to or exceeding virgin material costs [29][32];
Environmental Benefits: Coal fly ash valorization reduces landfill requirements, decreases groundwater contamination risk, and achieves ~80% lifecycle carbon footprint reduction compared to synthetic silica production [62];
Application Diversity: Coal fly ash-derived silica successfully addresses applications in environmental remediation (99%+ heavy metal removal), catalysis, advanced materials, and emerging energy storage sectors [29][49][50].

Technological Advancement Trends

Recent innovations advancing the field include:

- Microwave and ultrasonic-assisted synthesis: Reduced processing time and energy consumption
- Advanced thermal activation: Improved phase transformation and extraction efficiency
- Bioleaching approaches: Environmentally benign ambient-temperature processes
- Multi-product extraction: Simultaneous recovery of silica, alumina, and rare earth elements
- Composite material synthesis: Direct incorporation of coal fly ash into value-added products

Future Research Directions

Priority areas for continued investigation:

1. Process Scale-Up: Industrial demonstration plants integrating optimal extraction methodologies
2. Feedstock Standardization: Development of methods accommodating mineralogical variability
3. Energy Optimization: Reduced energy consumption through novel activation techniques
4. Rare Earth Recovery: Enhanced extraction and separation of valuable rare earth elements
5. Integration with Carbon Capture: Coupling fly ash utilization with carbon capture technologies
6. Circular Economy Implementation: Development of closed-loop processes minimizing waste streams
7. Quality Standardization: Establishment of international standards for coal fly ash-derived silica products

Policy and Regulatory Considerations

Acceleration of coal fly ash utilization requires:

- Regulatory Incentives: Tax benefits, grant programs, and regulatory requirements favoring fly ash utilization over landfilling
- Quality Standards: Development and adoption of international standards (ISO, ASTM) for silica and alumina products
- Environmental Regulations: Mandatory fly ash utilization targets in relevant sectors (construction, materials)
- Research Funding: Continued investment in process development and commercialization

Global Impact Potential

Implementation of comprehensive coal fly ash valorization strategies presents substantial opportunity [1][3]:

- Waste Reduction: Potential to utilize 200-300 million metric tons of currently-disposed fly ash annually
- Economic Value Creation: $10-15 billion annual value from recovered materials
- Environmental Remediation: Reduced contamination from fly ash storage, improved water and soil quality
- Sustainable Materials: Sourcing of high-value materials from industrial waste, supporting circular economy principles

REFERENCES

[1] Kuźnia, M. (2024). A Review of Coal Fly Ash Utilization: Environmental, Energy, and Material Assessment. *Energies*, 18(1), 52. https://doi.org/10.3390/en18010052

[2] Kumar, S., Kumar, R., & Bandopadhyay, A. (2006). Innovative methodologies for the utilization of wastes from metallurgical and allied industries. *Resources, Conversation and Reacycling*, 48(4), 301-314. https://doi.org/10.1016/j.resconrec.2006.03.003

[3] American Coal Ash Association. (2020). The U.S. Fly Ash Market: Production & Utilization Forecast. https://www.acaa-usa.org/

[4] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. *Progress in Energy and Combustion Science*, 36(3), 327-363. https://doi.org/10.1016/j.pecs.2009.11.003

[5] Blissett, R. S., & Rowson, N. A. (2012). A review of the multi-component utilisation of coal fly ash. *Fuel*, 97, 1-23. https://doi.org/10.1016/j.fuel.2012.03.024

[6] Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the composition and application of biomass ash. Part 1: Phase–mineral and chemical composition and classification. *Fuel*, 105, 19-39. https://doi.org/10.1016/j.fuel.2012.10.001

[7] Kim Hung Mo, Tung-Chai Ling. (2022). Utilization of coal fly ash and bottom ash in brick and block products. *Low carbon Stabilization and solidification of Hazardous Wastes.* 355-371. https://doi.org/10.1016/B978-0-12-824004-5.00026-8

[8] Fariha Kanwal, Ashfaq Ahmed, Farrukh Jamil, Sikander Rafiq, H. M. Uzair Ayub, Moinuddin Ghauri, M. Shahzad Khurram, Shahid Munir, Abrar Inayat, Muhammad S. Abu Bakar, Surendar Moogi, Su Shiung Lam, Young-Kwon park. (2021). Co-Combustion of blends of coal and underrutilised for environmental friendly electrical energy production. *Sustainability*, 13(9) 4881. https://doi.org/10.3390/su13094881

[9] Kristina M. Zierold, Clara G. Sears, John V. Myers, Guy N. Brock, Charlie H. Zhang, Lonnie Sears. (2022). Exposure to coal ash and depression in children aged 6-14 years old. (2022). *Environmental Research*, 214(3) 114005. https://doi.org/10.1016/j.envres.2022.114005

[10] Xing Long, Penghu Cao, Jun Luo, Hao Jiang, (2024). Stepwise extraction and utilization of silica and alumina from coal fly ash by mild hydrothermal process. *Process Safety and Environmental Protection*, 182, 918-929. https://doi.org/10.1016/j.psep.2023.12.035

[11] Jian-Ming Gao, Zhenwei Yan, Shujia, Yanxia Guo. (2024). Novel process for high value utilization of high-alumina fly ash: valuable metals recovery and mesoporous silica in situ preparation. *RSC Advances*, 14(3) 1782-1793. https://doi.org/10.1039/d3ra06921d

[12] Nozomu Hashimoto, Ryoichi Kurose, Hiromi Shirai. (2012). Numerical simulation of pulverized coal jet flame employing the TDP model. *Fuel*, 97, 277-287. https://doi.org/10.1016/j.fuel.2012.03.005

[13] Imoisili, P. E., Tien-Chien Jen. (2022). Microwave-assisted sol-gel template-free synthesis and characterisation of amorphous nano silica from South African coal fly ash. *Shynthesis of silica nanoparticles obtained from South African CFA*, 11, 3042-3052. DOI:10.1515/ntrev-2022-0476

[14] Marius Gheorghe Miricioiu, Violeta-Carolina Niculescu. (2020). Fly Ash, from Recycling to Potential Raw Material for Mesoporous Silica Synthesis. *Nanomaterials*, 13(4), 474. https://doi.org/10.3390/nano10030474

[15] Kentucky Geological Survey. (2025). Coal Combustion Byproducts. Retrieved from https://www.uky.edu

[16] ASTM International. (2017). ASTM C618-19: Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA.

[17] Juan Antonio Cecilia, Carmen Pilar Jimenez-Gomez. (2021). Catalytic applications of minerals and hydrotalcites. *Catalysts*, 11(1), 68. https://doi.org/10.3390/catal11010068

[18] Nurmalita, N., Herliansyah, M. K., & Humami, A. (2023). Characteristics of Silica Powder Extracted from Fly Ash of Coal Power Plant. *Journal of Ecological Engineering*, 24(9), 282-292. https://doi.org/10.12911/22998993/169289

[19] Prerna Sharma (2018). Self-Assembly of colloidal particles. *Resonance*, 263-275. https://doi.org/10.1007/s12045-018-0616-0

[20] Wang, W., Wang, Y., Yao, Q., Wilkinson, A., & Zhu, Y. (2023). Mechanical Activation of Coal Fly Ash for the Improvement of Alumina–Silica Separation During Reduction Roasting–Alkaline Leaching Process. *JOM*, 76, 1456-1466. https://doi.org/10.1007/s11837-023-06229-z

[21] Guangbin Liang, Yanghong Li, Chun Yang, Changyu Zi, Yuanqin Zhang, Xun Hu, Wenbo Zhao. (2020). Production of biosilica nanoparticles from biomass power plant fly ash. *Waste management*, 105, 8-17. https://doi.org/10.1016/j.wasman.2020.01.033

[22] Jakub Pulka, Piotr Manczarski, Pawel Stepien, Marzena Styczynska, Jacek A.Koziel, Andrej Bialowiec. (2020). Waste-to-xcarbon: Is the torrified sewage sludge wuth Ash content a better fuel or fertilizer? *Materials*, 13(4), 954. https://doi.org/10.3390/ma13040954

[23] Aadil Yousuf, Shahzada Manzoor, Mudasir Youssouf, Zubair A. Malik, Khawar Khawaja, (2022). Fly Ash Production and Utilization in India. *Journal of Materials and Environmental Science, 11(6) 911-921.* https://www.jmaterenvironsci.com/Document/vol11/vol11_N6/JMES-2020-1182-Yousuf.pdf

[24] 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. https://doi.org/10.1016/j.earscirev.2014.11.016

[25] Perwitasari, Heni Anggorowati, Uli Ulfa, Husna Muizzati Shabrina, Ahus Adhiatma. (2024). The Influence of aqua regia usage in the leaching and extraction process of silica from coal fly ash. (2024). *Equilibrium Journal of Chemical Engineering*, 8(1), 63-69. https://doi.org/10.20961/equilibrium.v8i1.86969

[26] Rosalina Hasan, Fatimah Mustafawi Muhammadi, Imas Solihat, Elisa Listianti, Muhammad Iskandar Ishaq, Yasinta Rahmatul Putri, Putri Alfiani. (2025). Nano-silica Derived from Coal Fly Ash: A Sustainable Iron (III) Ion Adsorbent *Journal of water derived from coal fly ash*, 10(3), 331-338. https://www.jwent.net/article_724130_f5cc0ccb4f46a96e3e48641a9349095b.pdf

[27] Aphane, M. E., Van Der Horst, J. M., & Muchatuta, I. (2020). Preparation of sodium silicate solutions and silica nanoparticles from coal fly ash waste. *Waste and Biomass Valorization*, 11, 4251-4261. https://doi.org/10.1007/s12649-019-00797-5

[28] Deshun Kong, Yuan Gao, Shuajiang Song, Rongli Jaing. Kinetics and mechanisms of SiO2 Extraction from Acid-leached coal gangue residue by alkaline hydrothermal treatment. *Materials*, 17(17), 4168. https://doi.org/10.3390/ma17174168

[29] Flavia Lega Braghiroli, Hassine Bouafif, Carmen Mihaela Neculita, Ahmed Koubaa. Influence of pyro-gasification and activation on the porosity of activated biochars: A literature review. (2019). *Waste and Biomass Valorization*, 11, 5079-5098. https://doi.org/10.1007/s12649-019-00797-5

[30] Chenliang Zhang, Yanheng Li, Qiaojing Zhao, Mingjing Xu, Bin Yao, Pengpeng Zhang, Xuan Ji, Jiawei Fan. (2025). High-efficiency extraction of lithium and aluminum from coal fly ash using activation-sintering technology. *Metals*, 15(2), 208. https://doi.org/10.3390/met15020208

[31] Aichun Zhao, Yujin Liu, Ting-an Zhang, Xin He, Xin Ye, Miao Zeng. (2022) Preparation of characterization of Portland cement clinker from sulfuric acid leaching residue of coal fly ash. *Materials research express*, 9(3), 035202. DOI:10.1088/2053-1591/ac4e3b

[32] H.Mori. (2003) Extraction of silicon dioxide from waste colored glasses by alkali fusion using potassium hydroxide. Journal of Amterial Science, 38, 3461-3468. https://doi.org/10.1023/A:1025100901693

[33] Huidong Liu. (2022). Conversion of harmful fly ash residue to zeolites: Innovative Processes focusing on maximum activation, Extraction, and Utilization of Aluminosilicate. (2022). *ACS Omega*, 7(23), 20347-20356. https://doi.org/10.1021/acsomega.2c02388

[34] Feng Yan, Jianguo Jiang, Sicong Tian, Zongwen Liu, Jeffrey Shi, Kaimin Li, Xuejing Chen, Yiwen Xu. (2016) A green and facile synthesis of ordered mesoporous nanosilica using coal fly ash. (2016). *ACS Sustainable Chemistry & Engineering*, 4(9), 4654-4661. https://doi.org/10.1021/acssuschemeng.6b00793

[35] Miaomiao Tan, Dahai Pan, Shuwei Chen, Xialiang Yan, Lina Han, Ruifeng, Li, Jianchneg Wang. (2023). Synthesis of Coal-fly-ash-based ordered Mesoporous materials and their adsorption application. *Materials*, 16(7), 2868. https://doi.org/10.3390/ma16072868

[36] Niculescu, V., Miricioiu, M., Enache, S., Constantinescu, M., Bucura, F., & David, E. (2019). Optimized method for producing mesoporous silica from incineration ash. *Smart Energy and Sustainable Environment*, 2(22), 65-76. https://www.energ-en.ro/pages/article/74

[37] Mathibela E. Aphane, Emile D. Maggot, Frederic J. Doucet, Selwyn F. Mapolie, Marile Landman, Elizabet M. van der merwe. (2024). Synthesis and Evaluation of Mesoporous Silica Nanoparticle Catalyst Supports Prepared from South African Coal Fly Ash. *Waste and Biomass Valorization*, 15, 5053-5068. https://doi.org/10.1007/s12649-024-02496-2

[38] Bin Deng, Wei Meng, Paul A. Advincula, Lucas Eddy, Mine G. Ucak-Astarlioglu, Kevin M. Wyss, Weiyin Chen & et.el. (2023) Heavy metal removal from coal ash for low carbon footprint cement. *Communications Engineering*, 2(13) https://doi.org/10.1038/s44172-023-00062-7

[39] Yadav, V. K., Abdelfattah Amari, Noureddine Mahdhi, Abubakr Mustafa Elkhaleefa.(2023). A novel and economical approach for the synthesis of short rod-shaped mesoporous silica nanoparticles from coal fly ash using Bacillus circulans MTCC 6811. *Journal of Materials Research and Technology*, 39, 289. https://doi.org/10.1007/s11274-023-03734-w

[40] Khan, S. A., Uddin, I., Moeez, S., & Ahmad, A. (2014). Fungus-Mediated Preferential Bioleaching of Waste Material Such as Fly-Ash as a Means of Producing Extracellular, Protein Capped, Fluorescent and Water Soluble Silica Nanoparticles. *PLOS One*, 9(9), e107597. https://doi.org/10.1371/journal.pone.0107597

[41] Production of Biosilica Nanoparticles from Biomass Power Plant Fly Ash. (2020). *Bioresource Technology*, 300, 122673. https://doi.org/10.1016/j.biortech.2019.122673

[42] Wang Hongyang, Wang Jiayao, Li Jianjun, Li Zhangshang, Wenhao Li, Mengdie Yang, Leiting Shen. (2023). Mechanical Activation of Coal Fly Ash for the Improvement of Alumina–Silica Separation During Reduction Roasting–Alkaline Leaching Process. *JOM*, 76, 1456-1466. https://doi.org/10.1007/s11837-023-06229-z

[43] Natalia Moreno, Xavier Querol, Felicia Plana, J. M. Andres, maria Janssen, Heng Nugteren. (2002). Pure zeolite synthesis from silica extracted from coal fly ashes. *Journal of Chemical Technology & Biotechnology*.77(3), 274-279. https://doi.org/10.1002/JCTB.578

[44] Gao, J., Yan, Z., Ma, S., & Guo, Y. (2024). Novel process for high value utilization of high-alumina fly ash: valuable metals recovery and mesoporous silica in situ preparation. *RSC Advances*, 14(3), 1782-1793. https://doi.org/10.1039/d3ra06921d

[45] Mokrzycki, J., Fedyna M., Duraczynska D., Martez M., Panek R., Wojciech F., Bajda T., Karcz R. (2024). Mesoporous Silica MCM-41 from Fly Ash as a Support of biometallic Cu/Mn catalysts for Toluene combustion. *Materials*, 17(3), 653. https://doi.org/10.3390/ma17030653

[46] Synthesis and Evaluation of Mesoporous Silica Nanoparticle Catalyst Supports Prepared from South African Coal Fly Ash. (2024). *Waste and biomass valorization*, 15, 5053-5068. https://doi.org/10.1007/s12649-024-02496-2

[47] Dandan Li, Hongyang Min, Xu Jiang, Ran Xianqiang. (2013) One-pot synthesis of Aluminum-containing ordered mesoporous silica MCM-41 using coal fly ash for phosphate adsorption. (2013). *Journal of colloid and interface science*, 404, 42-48 https://doi.org/10.1016/j.jcis.2013.04.018

[48] Efficient Activation of Coal Fly Ash for Silica and Alumina Leaches and the Dependence of Pb(II) Removal Capacity on the Crystallization Conditions of Al-MCM-41. (2021). *International journal of Molecular Sciences*, 22(12) 6540. https://doi.org/10.3390/ijms22126540

[49] Halina Misran, Ramesh Singh, Shahida Begum, Mohd A. Yarmo. (2007). Processing of mesoporous silica materials (MCM-41) from coal fly ash. (2007). *Journal materials processing technology*, 186(1-3) 8-13. https://doi.org/10.1016/j.jmatprotec.2006.10.032

[50] Xaohui Xu, Kaige Chen, Yong Dai, Xiaoping Xing, Lin Sun. (2025). Synthesis of Zeolite A–X from Coal Fly Ash via Ultrasonic-Alkali Fusion Hydrothermal Method for the Efficient Removal of Cr (VI) From Wastewater. (2025). *Water, Air & Soil Pollution*, 236, 137. https://doi.org/10.1007/s11270-025-07774-w

[51] Abdul Aziz, Rahmi, Lenny Marlinda. (2025). The Effect of Crystallization and Aging Time in Zeolite Synthesis Using Coal Fly Ash as Silica and Alumina Source. (2025). *Jurnal Teknologi*, 87(3). https://doi.org/10.11113/jurnalteknologi.v87.22254

[52] Thapelo manyepedza, Emmanuel V. Gaolefuga, Isaac N. Beas, Manoko Maubane-Nkadimeng, Moses T. Kabomo. (2025). ZSM-5 Zeolite Synthesis from Coal Fly Ash Synthesised Silica: Sole Silica & Alumina Source. (2025). *Chemistry Open*, 14(1), e202400042. https://doi.org/10.1002/open.202400314

[53] Jian-ming Gao, Shujia Ma, Bo Wang, Zhibin Ma, Yanxia Guo, Fangqin Cheng. Templete-free facile preparation of mesoporous silica from fly ash for shaped composite phase change materials. *Journal of Cleaner Production*, 384, 135583. https://doi.org/10.1016/j.jclepro.2022.135583

[54] Le Van Tam, Le Kien Anh, Nguyen Ky Phung. (2022). Effect of ultrasound on silicon extraction from coal fly ash. *Chemical Engineering Transactions*, 97. 145-150. https://doi.org/10.3303/CET2297025

[55] Borja Diaz de Grenu, Ruth de los Reyes, Ana M. Costero, Pedro Amoros, Jose Vicente Ros-Lis. (2020). Recent progress of microwave-assisted synthesis of silica materials. *Nanomaterials*, 10(6), 1092. https://doi.org/10.3390/nano10061092

[56] Rajaam Mohanty, Shantanu Kumar Mishra, Siba Shankar Mohapatra, Sasanka Chouhury, Biyanak Pattanayak. (2021). Extraction of Silica (SiO_2) from Coal Fly Ash by Leaching and Sintering Technology. *Advances in Thermofluids and Renewable Energy*, 389-395. https://doi.org/10.1007/978-981-16-3497-0_30

[57] Luvsandagva Mandakhsaikhan, Batmunkh Davaabal, Rentsennorov Ulambayar, Ochirkhuyag Altantuya, Tsoodol Zolzaya, Gendenjamts Oyun-Erdene. 2024). Research on reducing the iron minerals in the ash of thermal power plant ash ponds. *Bulletin of the institute of chemistr and chemical technology*, 185, 108197. https://doi.org/10.5564/bicct.v12i12.3937

[58] Zhiqing Wang, Jiejie Huang, Shaohua Ji, Yangang Mei, Yongwei Wang, Yitian Fang. (2017). Comparison of Silica Leaching Behaviors from the Acid-Leached Residue of Catalytic Gasification and Combustion. *Energy & Fuels*, 31(10), 10662-10745-10751. https://doi.org/10.1021/acs.energyfuels.7b01894

[59] Zhe Sun, Heyu Li, Zuimiao Tao, Baochuan Wang, Lei Gao, Yusheng Xu, Yan CaO. Investigation on the Value-Added Production of Silicon Dioxide and Synthesizing Zeolites as well as Extraction of Rare Earth Elements from Fly Ash. (2023). *Applied Sciences*, 13(2), 7250. https://doi.org/10.3390/app13127250

[60] Jie GU, Lipeng Liu, Rongrong Zhu, Qiqi Song, hanqing Yu, Pengjie Jiang, Changqing Miao & et.el. (2023). Recycling Coal Fly Ash for Super-Thermal-Insulating Aerogel Fiber Preparation with Simultaneous Al_2O_3 Extraction. *Molecules*, 28(24), 7979. https://doi.org/10.3390/molecules28247978

[61] Nakshatra B. Singh (2018) Fly ash-based geopolymer binder: A future construction material. *Minerals*, 8(7) 299. https://doi.org/10.3390/min8070299

[62] Guzide Kalyoncu Ergguler, Arash Dahi Taleghani. (2025). Geopolymer applications in deep-sea energy and mining infrastructure:a review of properties, challenges, and future prospects. *Environmental Earth Sciences*, 84, 345. https://doi.org/10.1007/s12665-025-12339-5

[63] Global Fly Ash Market Size, Share, Trends and Forecast to 2033. IMARC Group. (2024). Retrieved from https://www.imarcgroup.com