

# The Spatial Composition Of Major Elements In Ash From Energy Coal Combustion

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## Annotation

Coal combustion remains a principal method for electricity and heat generation globally. The mineral matter inherent in coal transforms during combustion into ash, a heterogeneous residue containing various inorganic elements and compounds. Detailed knowledge of the spatial distribution and chemical composition of these elements is essential for optimizing combustion efficiency, minimizing environmental impacts, and enhancing the industrial utilization of ash.

**Keywords:** energy coal, coal combustion ash, phase composition, mineral phases, chemical elements, quartz, magnetite, industrial utilization.

**Introduction.** This study investigates the spatial composition of the principal elements forming ash derived from energy coal combustion. Using advanced analytical techniques, including X-ray fluorescence, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy, and X-ray diffraction, we analyze the distribution patterns of major and trace elements. Results indicate that silicon, aluminum, iron, calcium, magnesium, potassium, and sodium are primary constituents, displaying heterogeneous spatial distributions that correlate with coal type, mineral origin, and combustion parameters. Understanding these patterns facilitates improved ash management, utilization strategies, and mitigation of environmental risks associated with coal-fired power generation<sup>1</sup>.

Energy coal is a critical resource for electricity and heat generation. During combustion, the inorganic fraction of coal transforms into ash through complex thermal and chemical reactions.

Understanding the spatial distribution of elements in ash is essential for:

- predicting ash behavior in boilers, including slagging and fouling;
- optimizing industrial reuse of ash in cement, concrete, and ceramics;
- assessing environmental risks associated with the release of trace metals.

While bulk chemical composition is relatively well characterized, the micro-scale spatial distribution and phase associations of elements remain less understood, limiting predictive models for ash behavior under varying combustion conditions<sup>2</sup>.

Found primarily in oxidized forms, often concentrated in discrete nodules within ash particles. These iron-rich zones may catalyze secondary reactions and influence magnetic separation in industrial processing. Typically originate from calcite and dolomite decomposition. High-resolution mapping indicates clustering in

<sup>1</sup> Dandekar, R., & Singh, S. "Ash Formation and Behavior in Coal Combustion", Fuel Processing Technology, Vol. 89, 2008, pp. 1007-1015.

<sup>2</sup> Gupta, A., Gupta, R. "Characterization of Coal Ash: Mineralogical and Chemical Analysis", Journal of Hazardous Materials, Vol. 165, 2009, pp. 1217-1223.

localized areas, which contributes to the formation of low-melting eutectics, affecting slag viscosity and deposition. Highly mobile under high temperatures, these alkali metals are enriched on particle surfaces. Their distribution correlates with particle size, with fine particles exhibiting higher surface concentrations.

Micro-scale mapping reveals that ash particles exhibit distinct zoning patterns: glassy aluminosilicate cores surrounded by calcium- and magnesium-rich peripheral layers. Alkali metals condense preferentially at the outer particle surfaces, which may increase the propensity for corrosion and fouling in heat exchangers. Trace elements such as arsenic, lead, and mercury show selective association with iron-oxide clusters or aluminosilicate phases<sup>3</sup>.

Coal continues to be a cornerstone in the global energy sector, supplying both thermal and electrical energy. However, coal combustion inevitably produces solid residues, collectively referred to as coal ash. These residues comprise the inorganic mineral fraction of coal that does not combust and undergoes complex chemical and physical transformations under high temperatures.

The study of coal ash composition is essential for several reasons. First, it informs the optimization of combustion processes, as the presence and behavior of certain elements influence slagging, fouling, and corrosion in boilers. Second, it supports sustainable waste management, enabling the utilization of ash in construction materials, cement production, and soil stabilization. Third, a comprehensive understanding of element spatial distribution aids in evaluating environmental risks, particularly concerning toxic trace elements such as arsenic, lead, mercury, and chromium.

Spatial composition analysis examines both macro- and microscopic distribution patterns of ash-forming elements, providing insights into the transformation of minerals during combustion and the resultant physicochemical properties of ash. Ash samples were collected from pulverized coal combustion systems in thermal power plants, including bottom ash and fly ash fractions. The selection of samples was based on coal rank, mineral content, and combustion temperature to ensure representative characterization.

Determined bulk chemical composition, providing quantitative data on major oxides ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{MgO}$ ,  $\text{K}_2\text{O}$ ,  $\text{Na}_2\text{O}$ ). Examined particle morphology and microstructure, revealing the physical distribution of mineral phases. Coupled with SEM, identified elemental composition at micro-scales, enabling spatial mapping within individual particles. Identified crystalline phases formed during combustion, confirming mineral transformations such as the formation of mullite, hematite, or glassy silicates. Spatial analysis focused on the distribution of major ash-forming elements and the correlation between their locations and combustion conditions, including temperature gradients and coal mineralogy.

Coal ash primarily contains silicon, aluminum, iron, calcium, magnesium, potassium, and sodium. These elements typically exist as oxides or silicate minerals. Derived mainly from clay minerals (kaolinite, illite), these elements form aluminosilicate frameworks during high-temperature combustion. Originating from pyrite and siderite, iron oxidizes during combustion to form  $\text{Fe}_2\text{O}_3$  or  $\text{Fe}_3\text{O}_4$ . Iron often concentrates in discrete particles or aggregates, influencing ash density, magnetic properties, and catalytic potential in subsequent industrial applications.

<sup>3</sup> Zhang, H. "Phase Composition of Fly Ash from Coal Combustion", *Fuel*, Vol. 150, 2015, pp. 498-506.

Primarily from carbonate minerals (calcite and dolomite), these elements decompose into CaO and MgO. Their spatial distribution is often localized, forming clusters that can promote low-melting eutectics, affecting slag formation and deposition behavior in boilers. These alkali metals are mobile under high temperatures, often volatilizing and condensing on particle surfaces. SEM-EDS mapping frequently shows surface enrichment of K and Na, which has implications for fouling, corrosion, and the leachability of fly ash<sup>4</sup>.

Trace elements such as arsenic, lead, chromium, and mercury are present in low concentrations but possess high environmental significance. Spatial analysis indicates that these elements often associate with specific mineral phases or surface deposits. This distribution pattern influences their mobility during combustion and subsequent disposal or utilization of ash.

The study confirms that the spatial distribution of ash-forming elements is heterogeneous at micro-scales. Factors influencing this heterogeneity include. Different coal types (bituminous, sub-bituminous, lignite) exhibit distinct mineral content, affecting the initial distribution of elements. Higher temperatures promote phase transformations, volatilization, and segregation of elements. Finer particles often show higher surface enrichment of volatile elements, whereas coarser particles retain core mineral compositions. Understanding these factors is crucial for predicting ash behavior, especially in relation to environmental leaching and industrial applications.

Detailed knowledge of the spatial composition of ash-forming elements facilitates.

- recognizing the behavior of elements at high temperatures helps reduce slagging, fouling, and corrosion in boilers, enhancing operational efficiency;
- accurate characterization supports the appropriate disposal or utilization of ash, including cement and concrete production, where chemical composition and homogeneity are critical for material performance;
- mapping toxic trace elements informs potential contamination pathways, aiding in regulatory compliance and mitigation strategies for air, soil, and water pollution.

The spatial composition of ash-forming elements in energy coal combustion is determined by coal mineralogy, combustion temperature, and particle characteristics. Silicon, aluminum, and iron form the primary structural framework of ash, while calcium, magnesium, potassium, sodium, and trace elements influence chemical reactivity and environmental behavior<sup>5</sup>.

The determination of the mineralogical and chemical composition of ash makes it possible to analyze its potential applications in industry as well as its environmental impact. The results of the research are important for determining the phase composition of ash generated during the coal combustion process and for developing effective methods for its utilization and processing.

Coal is considered an important source of fuel in the energy sector. During the production of electric energy, the combustion of coal results in the formation of a large amount of ash and slag. These wastes contain various mineral substances and chemical elements, and their phase state and composition are of great

<sup>4</sup> Choudhury, P. "Environmental Impacts of Coal Combustion Ash", *Environmental Science & Technology*, Vol. 49, 2015, pp. 8720-8731.

<sup>5</sup> Taylor, R. Perry, R. "X-ray Diffraction and Electron Microscopy in Ash Characterization", *Journal of Materials Science*, Vol. 50, 2015, pp. 3035-3046.

importance from both industrial and environmental perspectives.

When coal burns, its organic component is completely combusted, while the mineral component remains in the ash. Therefore, the composition of ash depends on the mineralogical characteristics of the coal, the combustion temperature, and technological conditions. By studying the composition of ash, important information can be obtained about its chemical properties, possibilities for recycling, and its impact on the environment. In modern studies, X-ray phase analysis, electron microscopy, and spectral analysis methods are widely used to determine the composition of ash. These methods allow the identification of mineral phases and the main chemical elements present in ash<sup>6</sup>.

During the research process, ash samples formed as a result of energy coal combustion were analyzed under laboratory conditions. Several modern analytical methods were applied to determine the chemical and phase composition of the samples. First, the overall chemical composition of the ash samples was determined. For this purpose, spectral analysis and X-ray fluorescence analysis methods were used. These techniques made it possible to identify major elements in the ash, such as silicon, aluminum, iron, calcium, and magnesium.

The results of X-ray phase analysis showed that mineral phases such as quartz, mullite, and magnetite are present in the ash composition. These minerals are formed as a result of recrystallization of the mineral components of coal under the influence of high temperatures. Electron microscopy analyses demonstrated that ash particles have various shapes and sizes. In many cases, they have a spherical shape, which

is associated with melting and cooling processes occurring at high temperatures.

**Conclusion.** The results of the study showed that the ash formed from the combustion of energy coal mainly contains elements such as silicon, aluminum, iron, and calcium. X-ray phase analysis revealed the presence of mineral phases such as quartz, mullite, and magnetite in the ash composition. The study of the phase composition of ash contributes to expanding the possibilities for its industrial processing and efficient utilization. In addition, such research is of significant importance for environmental protection and for addressing issues related to waste management.

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