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REVIEW ON PROCESSING COAL FLY ASH: CURRENT ADVANCES AND FUTURE PERSPECTIVES

Abstract: *This review aims to analyze the processing techniques employed for coal fly ash (CFA) and their implications. The study addresses the research problem of enhancing CFA utilization while minimizing environmental impacts. The review is based on the principles of sustainable development, circular economy, and resource conservation. It draws upon theories related to waste management, materials science, and environmental engineering. A systematic literature review was conducted, analyzing research articles, technical reports, and industry publications. The review encompasses a comprehensive examination of processing techniques, including separation, beneficiation, utilization, and treatment methods. The research*

techniques employed involved data synthesis and analysis of the identified studies. The review highlights the effectiveness and limitations of various processing techniques for CFA, such as electrostatic separation, magnetic separation, and froth flotation. It provides insights into the improvements achieved through processing, including enhanced CFA quality, expanded applications, and resource recovery. The findings emphasize the importance of comprehensive characterization of CFA, understanding its composition and properties, and optimizing processing methods to maximize its potential. The research contributes to the academic understanding of CFA processing techniques, providing a foundation for further studies in the field. Managerially, it offers guidance to industries involved in CFA utilization, promoting sustainable waste management practices and resource conservation. The review has significant social implications by reducing the environmental impact associated with CFA disposal and supporting the development of circular economy principles.
Key words: *coal fly ash, coal fly ash processing; physical separation; chemical separation; utilization of coal fly ash.*

1. Introduction

Coal fly ash (CFA) is a byproduct generated during the combustion of pulverized coal in coal-fired power plants. It is a fine, powdery material that is carried away with the flue gases and collected using electrostatic precipitators or bag filters [1-3].

The composition of CFA can vary depending on the type of coal burned and the combustion conditions. However, it generally consists of primarily inorganic materials such as silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO). It also contains smaller amounts of carbon, sulfur, heavy metals, and trace elements, which are present in the coal. The composition of CFA makes it suitable for various applications and processing methods. Understanding its composition is essential for efficient utilization and appropriate treatment to mitigate its environmental impact.

In addition to the inorganic components mentioned earlier, CFA may also contain minor amounts of organic matter, unburned carbon, and volatile compounds. Depending on factors such as the type and quality of coal used, furnace conditions, flue gas cleaning technology applied or afterconcombustion treatment, the particular composition of CFAs can be considerably different.

The CFA particle size distribution is usually fine, with a significant proportion of particles falling in the range of 1 to 100 micrometers [4,5]. This fine particle size contributes to its characteristic powdery nature and ease of transport through the flue gas.

Furthermore, CFA can exhibit various physical and chemical properties depending on its source. These properties include specific gravity, bulk density, particle shape, surface area, porosity, and reactivity. These characteristics influence the behavior and potential applications of CFA.

Due to its complex composition, CFA has garnered attention as both an environmental concern and a resource with economic potential. Effective processing techniques can help unlock the value of CFA, leading to its beneficial utilization in various industries such as cement and concrete production, construction materials, geopolymer synthesis, and environmental remediation.

Understanding the composition and properties of CFA is crucial for optimizing its processing methods, evaluating its potential applications, and developing sustainable solutions for its management.

The processing of CFA holds significant importance due to several reasons.

Processing techniques help in reducing the environmental impact by treating and managing CFA effectively. This includes reducing its volume, preventing the release of harmful constituents into the environment, and minimizing the potential for leaching of heavy metals and other contaminants [6-8].

CFA contains valuable components that can be recovered and utilized in various industries. Processing techniques enable the extraction of these valuable materials, such as silica, alumina, and iron, which can be used as raw materials in the production of cement, concrete, ceramics, and other construction materials [9-13]. Recovering these resources reduces the need for virgin raw materials, conserves natural resources, and promotes a circular economy approach.

This material can be used as a supplementary cementitious material in cement and concrete production [14-16]. By processing and incorporating fly ash into these applications, it can enhance the strength, durability, and workability of cementitious materials while reducing the demand for cement clinker. This leads to a significant reduction in carbon dioxide emissions associated with cement production, contributing to sustainable construction practices.

Processing CFA allows for the reduction of waste volumes and landfill requirements. By converting fly ash into value-added products or incorporating it into construction materials, the overall waste generation is minimized. This helps in conserving landfill space and reducing the environmental impact associated with waste disposal [17-20].

Utilizing CFA presents economic opportunities by transforming a waste material into a valuable resource [21-26]. The recovered materials can be sold or utilized in various industries, generating revenue and creating job opportunities. Additionally, the development and implementation of innovative processing technologies can drive technological advancements and promote economic growth in the field.

Overall, exploring CFA is significant in mitigating environmental impact, recovering valuable resources, promoting sustainable construction practices, minimizing waste, creating economic opportunities, and complying with regulatory requirements. Efficient processing techniques are essential for unlocking the potential of CFA and maximizing its value while ensuring environmental stewardship.

This review aims to provide a comprehensive analysis of the processing techniques employed for CFA. It will cover various aspects such as separation, beneficiation, utilization, and treatment methods and will be informative resource for researchers, engineers, policymakers, and other stakeholders interested in the processing of CFA.

2. Characterization of CFA

CFA possesses key characteristics that are crucial to comprehend for its processing and utilization. It is a finely divided material with a particle size distribution ranging from 1 to 100 micrometers, with the majority falling within the sub-micron to micrometer range. The fine particle size contributes to its powdery nature, influencing flowability and handling (Fig. 1)

CFA exhibits various physical properties including specific gravity, bulk density, particle shape, surface area, porosity, and reactivity. Specific gravity refers to its density relative to water, while bulk density relates to mass per unit volume. Particle shape can range from spherical to irregular, influenced by the combustion process. Surface area and porosity impact reactivity and adsorption properties.

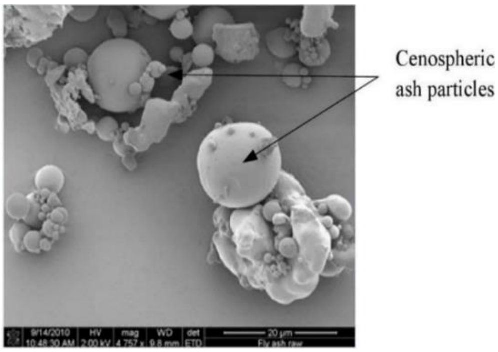

Figure 1 – The structure of CFA showing the surface morphology as cenospheric ash particles

Pozzolanic activity is a notable property of CFA, enabling it to react with calcium hydroxide in the presence of moisture, forming additional cementitious compounds [28]. This characteristic makes fly ash suitable as a supplementary cementitious material in cement and concrete applications. The pozzolanic activity varies based on composition, fineness, and processing history.

CFA possesses thermal properties influenced by the combustion process [29]. It exhibits a relatively high specific heat capacity, affecting its thermal behavior and potential applications in thermal management.

Leachability refers to the potential release of contaminants, such as heavy metals and trace elements, from CFA into the environment under specific conditions [30, 31]. Leachability depends on factors like fly ash composition, pH, and the presence of leaching agents. Understanding leaching characteristics is crucial for proper management and utilization, minimizing environmental impacts.

Depending on coal source and combustion conditions, CFA may contain magnetic components like iron oxides [32]. These magnetic properties can be utilized in magnetic separation processes for fly ash beneficiation and metal recovery.

Reactivity denotes the ability of CFA to chemically react with other substances. It is influenced by factors such as composition, particle size, and surface area. Reactive fly ash can participate in chemical reactions and contribute to the strength development, durability enhancement, and other beneficial properties of cementitious materials.

CFA exhibits electrical conductivity due to its composition and the presence of conductive minerals [33]. This electrical conductivity impacts its behavior in electrostatic separation processes and electrochemical applications.

Commonly gray or off-white in color, the color of fly ash can vary based on coal source and combustion conditions. Color influences its potential applications, including use as pigments, fillers, and decorative concrete.

During cement hydration, CFA undergoes hydration reactions with calcium hydroxide when used as a cement replacement or additive. The hydration characteristics, such as reaction rate and extent, influence the development of strength, setting time, and other properties of cementitious materials.

CFA may contain trace elements and heavy metals present in the coal [34]. The presence and concentration of these constituents vary depending on factors such as coal quality and combustion conditions. Understanding their content and behavior is crucial for assessing potential environmental and health impacts associated with fly ash processing and utilization.

3. Separation Techniques

Physical and chemical methods are commonly employed for separating the components of CFA. These methods aim to isolate specific constituents or fractions based on their physical or chemical properties.

Physical Separation Techniques:

- Electrostatic Separation: Electrostatic separation utilizes the differences in electrical conductivity and chargeability of the components in CFA [35-37]. It involves applying electrostatic forces to separate charged particles based on their electrostatic properties.
- Magnetic Separation: Magnetic separation exploits the magnetic properties of certain components in fly ash. By subjecting the fly ash to a magnetic field, magnetic particles can be separated from non-magnetic ones, aiding in the removal of iron-rich fractions [38, 39].
- Froth Flotation: Froth flotation utilizes the differences in surface hydrophobicity between components. By introducing air bubbles into a suspension of fly ash particles, hydrophobic components can selectively attach to the bubbles and be separated from the hydrophilic components [40-43].
- Gravity Separation: Gravity separation exploits the differences in density between various components in CFA [44]. The heavier components can settle or be separated from the lighter ones when the fly ash is subjected to gravitational forces. Gravity separation is the use of settling, sedimentation andcentrifugation. These methods are particularly effective for separating coarse particles or dense components, such as unburned carbon or heavy minerals.
- Sieving and Classification: Sieving and classification methods involve the use of screens or classifiers to separate fly ash particles based on their size or particle size distribution [45]. Sieving is commonly used to separate coarse and fine fractions of fly ash, while classifiers can sort particles based on their size or shape.

Chemical Separation Techniques:

- Acid Leaching: Acid leaching involves treating fly ash with acid solutions to selectively dissolve specific components [46-48]. This technique is often employed to remove or recover certain metals or metalloids from fly ash.
- Alkali Activation: Alkali activation, also known as alkaline extraction or alkaline leaching, utilizes alkaline solutions to extract specific components from fly ash (Fig. 2). It is often used to recover valuable metals, such as aluminum and silica, for further utilization.

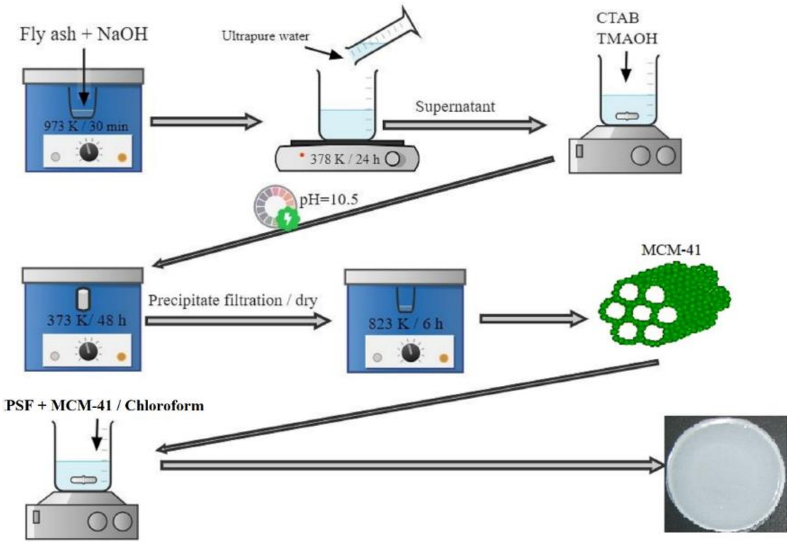

Figure 2 – Coal fly ash processing by using alkali activation

- Solvent Extraction: Solvent extraction employs organic solvents to selectively extract components from fly ash based on their solubility in specific solvents [50-52]. This technique can be useful for separating organic compounds or specific metals from the fly ash matrix.
- Flotation: Flotation is a physical-chemical separation technique that utilizes the differences in surface wettability of particles. By introducing flotation reagents and creating froth, hydrophobic particles can attach to air bubbles and rise to the surface, while hydrophilic particles remain in the liquid phase. Flotation can be used to separate carbon-rich fractions or specific minerals from the fly ash [53].

These physical and chemical separation techniques offer a range of options for effectively separating the components of CFA. The selection of the most suitable technique depends on the specific objectives, composition of the fly ash, particle size distribution, and the desired outcomes of the separation process. Combining multiple methods in a processing scheme can enhance separation efficiency and enable the recovery of valuable components while minimizing waste and environmental impact.

3. Utilization of CFA

CFA has a wide range of diverse applications across various industries due to its unique properties and characteristics (Fig. 3).

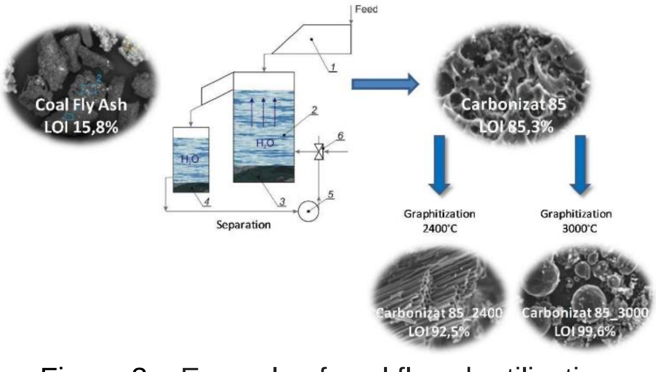

Figure 3 – Example of coal fly ash utilization

Cement and Concrete Production: CFA is extensively used as a supplementary cementitious material (SCM) in cement and concrete production [55, 56]. It improves the workability, strength, durability, and long-term performance of concrete. Fly ash reduces the need for clinker, the main component of cement, thereby reducing carbon dioxide emissions associated with cement production. It also enhances the sustainability and resource efficiency of the construction industry.

Construction Materials: Fly ash is utilized in the manufacture of various construction materials [57, 58]. It can be used as a partial replacement for cement in the production of mortar, grout, and plaster. Additionally, it is incorporated into bricks, blocks, and precast concrete products to enhance their properties and reduce material and energy consumption.

Geopolymer Synthesis: CFA is a key ingredient in geopolymer technology, where it acts as a precursor for the formation of inorganic polymers [59-62]. Geopolymers offer an alternative to traditional cementitious materials and can be used in the production of high-strength, durable, and environmentally friendly construction materials.

Road Construction: Fly ash can be used as a stabilizing agent in road construction. It improves the strength and stability of the subgrade, reduces the risk of cracking, and mitigates the swelling and shrinking of clay soils [63, 64]. Fly ash is also utilized as a filler material in asphalt mixes to enhance their performance and longevity.

Waste Stabilization and Remediation: CFA is used for waste stabilization and remediation purposes [65]. It can be employed to immobilize and stabilize hazardous waste materials, preventing the leaching of contaminants into the environment. Fly ash can also be used in landfill liners, capping systems, and for the remediation of contaminated soils and water.

Agricultural Applications: Fly ash can be utilized in agricultural practices as a soil amendment [66]. It improves soil fertility, enhances nutrient retention, and promotes plant growth. Additionally, fly ash can be used for land reclamation and ecological restoration projects.

Environmental Applications: Fly ash is employed in environmental applications, such as flue gas desulfurization (FGD) systems, where it is used as an absorbent for sulfur dioxide (SO_2) removal [67]. It is also utilized in air pollution control technologies, such as activated carbon production and mercury capture.

Waste-to-Energy and Biomass Applications: Fly ash from the combustion of biomass and waste materials can be utilized in similar applications as CFA [68]. It can be used as a cementitious material, in construction materials, or for waste stabilization.

The diverse applications of CFA demonstrate its versatility and value as a resource. By utilizing fly ash in these applications, it promotes resource conservation, reduces waste generation, and contributes to sustainable development practices across various industries.

6. Environmental and Economic Perspectives

Environmental Implications of CFA Processing:

CFA processing can have both positive and negative environmental implications. It is essential to carefully manage and mitigate these impacts. Some key environmental considerations include:

- Air Pollution: The processing of CFA can release dust and particulate matter into the air, contributing to air pollution. Proper dust control measures and air filtration systems are necessary to minimize emissions during processing operations.
- Water Contamination: Improper storage or disposal of fly ash can lead to water contamination through leaching of contaminants, including heavy metals and trace elements, into groundwater or surface water bodies. Effective management strategies, such as containment and leachate collection systems, are important to prevent water pollution.
- Land Use and Waste Management: Fly ash processing generates residues or byproducts that require appropriate waste management practices. The disposal of these residues in landfills must meet regulatory requirements to prevent potential environmental impacts. Implementing sustainable waste management practices, such as beneficial utilization or recycling, can help minimize the need for landfilling.
- Energy Consumption and Greenhouse Gas Emissions: Some processing techniques may require significant energy inputs, contributing to greenhouse gas emissions. The energy sources and efficiency of the processing operations should be considered to minimize the carbon footprint associated with fly ash processing.

To mitigate these environmental implications, it is crucial to implement strict regulatory frameworks, employ advanced pollution control technologies, promote recycling and reuse of fly ash, and adopt sustainable practices throughout the processing and utilization chain.

Economic Viability of Different Processing Techniques

The economic viability of CFA processing techniques depends on several factors, including the scale of operations, market demand, cost of inputs, and potential revenue streams. The following aspects should be considered when evaluating the economic viability:

- Cost-Benefit Analysis: Assessing the costs associated with processing, such as equipment, energy consumption, labor, and waste management, compared to the potential economic benefits of the processed fly ash is essential.
- Revenue generation: In order to help the processing techniques be economically viable, it is possible to identify new sources of income from treated fly ash such as sales of value added products, use in different sectors or carbon offsets.
- Market demand and prices considerations: the determination of market demand for processed fly ash products and evaluating price dynamics can help assess the economic feasibility of different processing techniques.
- Cost Reduction Strategies: Exploring cost reduction strategies, such as process optimization, technology advancements, and resource efficiency, can enhance the economic viability of fly ash processing operations.

Resource Recovery and Circular Economy Principles

Fly ash processing offers opportunities for resource recovery and aligns with circular economy principles. By treating and processing fly ash, the following benefits can be achieved:

- Recovery of Valuable Materials: Fly ash contains valuable components, such as silica, alumina, and iron, which can be recovered and utilized in various industries. Resource recovery from fly ash reduces the demand for virgin raw materials, conserves natural resources, and promotes a circular economy approach.
- Waste Minimization: Processing fly ash can reduce the volume of waste requiring disposal, minimizing the need for landfill space and associated environmental impacts. Utilizing fly ash as a resource reduces waste generation and supports sustainable waste management practices.
- Closed-Loop Systems: Adopting closed-loop systems, where the byproducts or residues from fly ash processing are recycled or utilized within the same or related industries, promotes circular economy principles. This approach maximizes the value and utility of fly ash, minimizing waste and reducing the environmental footprint.
- Environmental Benefits: The proper processing and utilization of fly ash contribute to environmental benefits, including reduced greenhouse gas emissions, decreased reliance on virgin resources, and improved waste management practices.

By implementing resource recovery strategies and embracing circular economy principles, fly ash processing can transform a waste material into a valuable resource while minimizing environmental impacts and promoting sustainable development.

7. Challenges and Future Directions

Challenges

CFA composition can vary significantly depending on factors such as the coal source, combustion conditions, and flue gas cleaning systems. This variability presents challenges in developing standardized processing techniques that can effectively handle the diverse compositions of fly ash.

Scaling up fly ash processing techniques to meet large-scale production demands while maintaining efficiency and cost-effectiveness is a challenge. Developing processing methods that can handle high volumes of fly ash without compromising the quality of the processed material is crucial.

There are challenges in balancing the need for efficient processing and environmental considerations. Important aspects to be taken into account are the proper management of waste streams, minimising air and water pollution as well as the potential for contamination from fly ash processing plants.

Keeping up with technological advancements and adopting innovative processing techniques can be a challenge in the field of fly ash processing. Research and development efforts are needed to explore and implement new technologies that can improve the efficiency, effectiveness, and sustainability of fly ash processing.

Knowledge gaps

Further research is needed to enhance the understanding of the composition, physical properties, and behavior of different fly ash types. This will enable the development of more targeted and effective processing techniques based on specific fly ash characteristics.

More research is required to optimize existing processing techniques and develop new methods to enhance the separation efficiency, purity, and quality of the processed fly ash fractions. This includes improving the selectivity, yield, and cost-effectiveness of separation methods.

Investigating innovative ways to utilize the byproducts and residues generated during fly ash processing can help minimize waste and enhance the economic viability of the overall process. Finding value-added applications for these byproducts will contribute to a more sustainable and circular approach.

Conducting comprehensive and systematic assessments of the environmental impacts associated with different processing techniques is crucial. This includes evaluating air emissions, water contamination risks, and the potential for resource depletion, to develop strategies for minimizing environmental footprints.

Future Directions and Emerging Technologies

Improved separation efficiency, selectivity and purity of fly ash fractions can be achieved through further research on the latest technology for separating such as ionising separators, highgradient magnetic separaters and advanced flotation methods.

Future directions in fly ash processing involve exploring more sustainable utilization pathways, such as increased use of fly ash in high-value products, development of novel applications, and integration fly ash into circular economy practices.

Research efforts are focusing on utilizing fly ash as a sorbent for carbon capture, contributing to the reduction of greenhouse gas emissions. Developing efficient carbon capture and utilization technologies using fly ash can enhance its environmental and economic value.

Investigating the use of processed fly ash in the development of advanced composite materials, such as geopolymers, engineered aggregates, and lightweight construction materials, offers promising avenues for future applications.

Integrating fly ash processing with other industrial processes, such as coal combustion, cement production, or waste-to-energy facilities, can create synergies, enhance resource efficiency, and improve overall sustainability.

Addressing the current challenges, conducting further research to fill gaps in knowledge, and exploring emerging technologies will pave the way for more efficient, sustainable, and value-added CFA processing. Future directions involve a multidisciplinary approach that considers technical, environmental, and economic aspects to maximize the potential of this abundant waste material.

8. Conclusion

CFA is a valuable byproduct produced by the burning of coal at power plants. It consists of fine particles primarily composed of silica, alumina, iron oxide, and calcium oxide. Processing CFA holds significant importance for various reasons.

It enhances the utilization of this waste material, reducing the need for landfilling and promoting sustainable waste management practices. By processing fly ash, its potential applications can be expanded, leading to increased value and reduced waste generation.

Processing improves the quality and properties of fly ash, making it suitable for a wider range of applications. This includes enhancing its strength, durability, and other performance characteristics, making it valuable in industries such as cement and concrete production, construction, road construction, waste stabilization, and agriculture.

Moreover, processing CFA contributes to resource conservation. Valuable components present in the fly ash can be recovered and utilized, reducing the reliance on virgin raw materials. This not only conserves natural resources but also reduces the environmental impact associated with their extraction and processing.

Fly ash processing promotes sustainable development by reducing environmental impacts and supporting circular economy principles. It minimizes the release of fly ash into the environment, mitigating air and water pollution risks. By treating fly ash as a resource and incorporating it back into the production cycle, it supports the circular economy concept of minimizing waste and maximizing resource efficiency.

The provided review an overview of various characteristics of CFA, including particle size distribution, chemical composition, mineralogy, reactivity, and leachability. It also discussed the effectiveness and limitations of processing techniques such as electrostatic separation, magnetic separation, and froth flotation for separating fly ash components. Furthermore, the review explored the diverse applications of CFA in industries such as cement and concrete production, construction materials, road construction, waste stabilization, and agriculture.

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ОБЗОР ПО ПЕРЕРАБОТКЕ УГОЛЬНОЙ ЛЕТУЧЕЙ ЗОЛЫ: ТЕКУЩИЕ ДОСТИЖЕНИЯ И ПЕРСПЕКТИВЫ НА БУДУЩЕЕ

Целью данного обзора является анализ методов переработки угольной летучей золы (УЛЗ) и их последствий. В исследовании рассматривается исследовательская проблема повышения эффективности использования УЛЗ при минимизации воздействия на окружающую среду. Обзор основан на принципах устойчивого развития, экономики замкнутого цикла и ресурсосбережения. Он опирается на теории, связанные с обращением с отходами, материаловедением и инженерной экологией. Был проведен систематический обзор литературы, проанализированы исследовательские статьи, технические отчеты и отраслевые публикации. Обзор включает всестороннее изучение методов переработки, включая разделение, обогащение, утилизацию и методы обработки. Используемые методы исследования включали синтез данных и анализ выявленных исследований. В обзоре освещаются эффективность и ограничения различных методов обработки УЛЗ, таких как электростатическая сепарация, магнитная сепарация и пенная флотация. В нем представлена информация об улучшениях, достигнутых в результате обработки, включая повышение качества УЛЗ, расширение сферы применения и рекуперацию ресурсов. Полученные результаты подчеркивают важность всесторонней характеристики УЛЗ, понимания его состава и свойств, а также оптимизации методов обработки для максимизации его потенциала. Исследование способствует академическому пониманию методов обработки УЛЗ, обеспечивая основу для дальнейших исследований в этой области. С управленческой точки зрения он предлагает рекомендации отраслям, участвующим в утилизации УЛЗ, продвигая устойчивые методы обращения с отходами и ресурсосбережения. Обзор имеет значительные социальные последствия, поскольку снижает воздействие на окружающую среду, связанное с утилизацией УЛЗ, и поддерживает развитие принципов экономики замкнутого цикла.

Ключевые слова: *угольная летучая зола, переработка угольной летучей золы, физическое разделение, химическое разделение, утилизация угольной золы.*

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КӨМІР КҮЛІН ҚАЙТА ӨҢДЕУГЕ ШОЛУ: АҒЫМДАҒЫ ЖЕТІСТІКТЕР МЕН БОЛАШАҚ ПЕРСПЕКТИВАЛАР

Бұл шолудың мақсаты көмір күлін (КК) өңдеу әдістерін және олардың салдарын талдау болып табылады. Зерттеу қоршаған ортаға әсерді азайту кезінде КК пайдалану тиімділігін арттырудың зерттеу мәселесін қарастырады. Шолу тұрақты даму, айналмалы экономика және ресурстарды үнемдеу принциптеріне негізделген. Ол қалдықтарды басқару, материалтану және инженерлік экологияға қатысты теорияларға сүйенеді. Әдебиеттерге жүйелі шолу жасалды, ғылыми мақалалар, техникалық есептер және салалық басылымдар талданды. Шолу қайта өңдеу әдістерін, соның ішінде бөлуді, байытуды, жоюды және өңдеу әдістерін жан-жақты зерттеуді қамтиды. Қолданылатын зерттеу әдістері Деректерді синтездеуді және анықталған зерттеулерді талдауды қамтыды. Шолу электростатикалық сепарация, магниттік сепарация және көбік флотациясы сияқты КК өңдеудің әртүрлі әдістерінің тиімділігі мен шектеулерін көрсетеді. Онда өңдеу нәтижесінде қол жеткізілген жақсартулар, соның ішінде КК сапасын арттыру, қолдану аясын кеңейту және ресурстарды қалпына келтіру туралы ақпарат берілген. Нәтижелер КК жан-жақты сипаттамасының, оның құрамы мен қасиеттерін түсінудің, сондай-ақ оның әлеуетін арттыру үшін өңдеу әдістерін оңтайландырудың маңыздылығын көрсетеді. Зерттеу осы саладағы Қосымша зерттеулерге негіз бола отырып, КК өңдеу әдістерін академиялық түсінуге ықпал етеді. Басқару тұрғысынан ол қалдықтарды басқару мен ресурстарды үнемдеудің тұрақты әдістерін насихаттай отырып, КК жоюға қатысатын салаларға ұсыныстар ұсынады. Шолудың айтарлықтай әлеуметтік

салдары бар, өйткені ол КК жоюға байланысты қоршаған ортаға әсерді азайтады және айналмалы экономика принциптерінің дамуын қолдайды.

Түйін сөздер: *көмір күлі, көмір күлін қайта өңдеу, физикалық бөлу, химиялық бөлу, көмір күлін кәдеге жарату.*

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СИНТЕЗ И ИССЛЕДОВАНИЕ ГИБРИДНЫХ НАНОТРУБОК ПЕРОВСКИТА $SrTiO_3$/ TiO_2 МЕТОДОМ ЭЛЕКТРОХИМИЧЕСКОГО АНОДИРОВАНИЯ

Аннотация: *Слои нанотрубок TiO_2, сформированных в процессе анодирования, представляют собой область активных исследований в контексте инновационных систем конвертации и накопления энергии. Титановые нанотрубки (TNT) привлекают внимание благодаря своим уникальным свойствам, особенно высокому отношению поверхности к объему, что делает их желанным материалом для различных технологических приложений. Метод анодирования широко используется для производства TNT из-за его простоты и относительной дешевизны, метод*