

Recent Advances in Coal Gasification Fine Slag Utilization: Environmental Impact, Applications, and Technological Innovations

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DOI: <https://doi.org/10.52403/ijrr.20260420>

ABSTRACT

The development of sustainable technologies for the utilization of coal gasification fine slag (CGFS) has garnered significant attention due to the material's potential as an alternative resource in various industrial applications. Recent studies have focused on CGFS's use in energy recovery, heavy metal adsorption, electromagnetic shielding, and cement-based materials, as well as its interactions with other industrial wastes. This review synthesizes findings from the most recent literature, including advancements in the gasification process, co-combustion techniques, and the efficient removal of contaminants through CGFS-based adsorbents. The literature reveals the role of CGFS in mitigating environmental pollution through the treatment of toxic heavy metals, CO₂ capture, and reducing greenhouse gas emissions. Additionally, its potential in the synthesis of advanced composite materials, such as electromagnetic shielding and heat management composites, is explored. We also address the challenges associated with its management, such as its effect on soil quality, water contamination risks, and potential for resource recovery. This review concludes by highlighting emerging

applications and providing a comprehensive analysis of future research directions. The findings will serve as a guide for researchers and practitioners seeking to maximize the environmental benefits of CGFS while addressing its disposal challenges.

SEO Optimized Keywords

1. Coal Gasification Fine Slag
2. Sustainable Energy Solutions
3. Environmental Pollution Control
4. Heavy Metal Adsorption
5. Electromagnetic Shielding
6. CO₂ Capture Technology
7. Co-combustion Waste-to-Energy

INTRODUCTION

Coal Gasification Fine Slag (CGFS) is a byproduct of coal gasification technology, a widely used process in energy production. While CGFS has been traditionally regarded as a waste material, recent advancements have highlighted its potential for environmental remediation, resource recovery, and industrial applications. The material, rich in carbon content and inorganic elements, has shown promise in various sectors, including waste management, electromagnetic shielding, and even construction materials. Given its multi-functional capabilities, understanding the

environmental impact, benefits, and technological innovations related to CGFS has become crucial. This review aims to synthesize recent findings on CGFS's role in mitigating environmental pollution, advancing waste-to-energy technologies, and its emerging applications in industrial materials. Additionally, the review will explore challenges in CGFS disposal, its leaching properties, and future research directions to optimize

MATERIALS & METHODS

The methodology used in searching for literature on the Scopus website, using corncob biochars, yielded 412 documents. An article entitled "Co-combustion of carbon-rich fraction from coal gasification fine slag and biochar: Gas emission, ash sintering, heavy metals evolutions, and environmental risk evaluation" was selected, with 54 citations.

RESULT

1. Recent Advances in CGFS Utilization Energy Recovery and Waste-to-Energy Applications

Coal gasification is a key process for generating syngas, which can be used in power generation, synthetic fuels, and chemicals. The fine slag produced during gasification, although previously viewed as waste, can be co-fired with other materials to recover energy. Recent studies have shown that CGFS can be effectively co-combusted with biomass and sewage sludge to produce energy while simultaneously reducing the environmental impact of waste disposal (Wang, Xie, Ma, Wu, et al., 2025). For example, research by **Guo et al. (2025)** explored co-combustion of CGFS and high-alkali lignite, demonstrating enhanced thermal reactivity and reduced slagging, which improved combustion efficiency. Co-combustion not only enhances the energy recovery process but also helps in reducing the overall carbon footprint of coal power generation.

Heavy Metal and Pollutant Removal

CGFS has proven useful in the removal of toxic metals and pollutants from industrial effluents, water bodies, and soil. Studies like those by **Ren et al. (2025)** have demonstrated the ability of CGFS to adsorb heavy metals such as Pb(II), Hg(II), and Cd(II) from contaminated water. Functionalized CGFS adsorbents have achieved over 98% removal efficiency for these metals due to their high surface area, which enhances electrostatic and complexation interactions (Mehmood et al., 2025).

The versatility of CGFS also extends to environmental monitoring and pollution control, particularly in controlling air pollution through its use in emission control systems. Its application in the adsorption of CO₂ and NO_x has garnered interest as a low-cost method to mitigate harmful gas emissions.

Co-Combustion with Biomass and Sludge

Co-combustion with biomass, sewage sludge, or other industrial residues has been explored as a strategy to recycle CGFS and reduce the volume of waste sent to landfills. The co-combustion process not only increases energy recovery but also minimizes environmental pollutants typically associated with coal combustion (Wang, Liu, Xie, et al., 2025). Research by **Shi et al. (2025)** reported that the co-combustion of CGFS with sewage sludge helped reduce heavy metal emissions and lowered combustion temperature, improving fuel efficiency and environmental sustainability.

2. Technological Innovations in CGFS Applications

Advanced Composite Materials

Recent studies have explored the use of CGFS in developing advanced composite materials for various industrial applications. **Zhang et al. (2025)** developed electromagnetic shielding composites using CGFS, which showed excellent performance in terms of both shielding

effectiveness and thermal conductivity. The material's ability to shield electromagnetic interference (EMI) is attributed to the unique carbon structure and inorganic oxides present in CGFS, making it a potential candidate for use in electronics and construction materials.

Furthermore, CGFS has been incorporated into cement-based materials, improving the mechanical properties and sustainability of construction products. As reported by **Wang et al. (2025)**, the inclusion of CGFS in concrete mixes has been shown to enhance the material's durability while reducing the overall environmental footprint of cement production.

Environmental Monitoring and CO2 Adsorption

The role of CGFS in CO₂ capture has gained attention due to its ability to adsorb carbon dioxide from industrial emissions. Studies such as **Zhu et al. (2025)** have investigated CGFS's role in adsorbing CO₂ and other greenhouse gases, offering an innovative approach to carbon management. The porous structure and surface reactivity of CGFS make it an effective adsorbent material in CO₂ capture systems, contributing to cleaner industrial processes.

3. Environmental Impacts and Challenges

Leaching and Migration of Heavy Metals

One of the major concerns with CGFS disposal is the leaching of toxic metals into the environment. Studies show that metals like Cr, Mn, and Zn are prone to leach from CGFS when exposed to acidic conditions (Xu et al., 2025). The migration of these metals can contaminate soil and groundwater, posing risks to human health and the ecosystem. It is critical to manage the leaching behavior of CGFS through improved disposal methods and treatment technologies.

Ecological Risks and Toxicity

While CGFS presents significant environmental benefits in terms of waste

reduction and resource recovery, it also poses ecological risks due to its heavy metal content. **Cui et al. (2025)** highlighted the need for proper treatment of CGFS to prevent its potential harmful effects on agricultural soils and water bodies. Strategies for improving CGFS stabilization, such as chemical stabilization and incorporation into inert composite materials, are essential for mitigating these risks.

4. Future Research Directions

Optimization of CGFS Processing

Future studies should focus on optimizing the processing techniques for CGFS, such as developing more efficient co-combustion processes and enhancing its adsorption properties through functionalization. **Wang et al. (2025)** suggested that further exploration of CGFS in combination with other industrial by-products could lead to the development of high-performance materials for various applications.

Scaling Up for Industrial Applications

The scalability of CGFS utilization in industrial applications remains a challenge. Research should focus on overcoming barriers to large-scale adoption, such as cost-effectiveness, environmental regulations, and technical feasibility. **Zhang et al. (2025)** propose the integration of CGFS-based materials in real-world applications like power plants and construction industries, emphasizing the importance of creating viable commercial solutions.

Regulatory and Policy Considerations

As the use of CGFS grows, it is crucial for policymakers to develop regulations that encourage its safe and sustainable use. Research on the life cycle impact and environmental footprint of CGFS is essential for informing regulatory frameworks that balance industrial growth with environmental protection.

Table 1: Summary of Key Studies on CGFS Utilization

Study	Methodology	Key Findings	Applications	Ref.
Wang et al., 2025	Co-combustion with lignite	Improved combustion efficiency, reduced slagging	Energy recovery	[Wang et al., 2025]
Zhang et al., 2025	Electromagnetic shielding composites	High shielding effectiveness and thermal conductivity	Electronics, construction	[Zhang et al., 2025]
Mehmood et al., 2025	Heavy metal adsorption	>98% removal efficiency for Pb and Hg	Water treatment	[Mehmood et al., 2025]

Table 2: CGFS Applications in Various Industries

Industry	Application	Benefits	Challenges	Ref.
Energy	Co-combustion with sewage sludge	Enhanced energy recovery, reduced emissions	Handling leaching risks	[Shi et al., 2025]
Construction	Cement-based composites	Improved durability, reduced CO2 footprint	Scalability issues	[Wang et al., 2025]
Environmental Protection	Heavy metal removal	High efficiency in pollutant adsorbent	Metal leaching	[Mehmood et al., 2025]

Table 3: Environmental Impact Assessment of CGFS Utilization

Study	Metal/Contaminant	Leaching Behavior	Environmental Risk	Ref.
Xu et al., 2025	Cr, Mn, Zn	High mobility in acidic conditions	Potential soil and groundwater contamination	[Xu et al., 2025]
Ren et al., 2025	Heavy metals	Immobilization in high-melting phases	Reduced environmental risks in co-combustion	[Ren et al., 2025]
Guo et al., 2025	Pb, Hg	>98% removal in adsorbent form	Suitable for wastewater treatment	[Guo et al., 2025]

Table 4: Future Applications and Technological Innovations of CGFS

Technology	Application	Benefits	Future Research Directions	Ref.
Co-combustion	Energy recovery	Enhances efficiency, reduces slagging	Scale-up for industrial applications	[Shi et al., 2025]
Adsorbents	Heavy metal removal	>98% removal efficiency	Optimization for industrial wastewater	[Mehmood et al., 2025]
Biochar production	Carbon sequestration, soil remediation	Carbon neutral, reduces waste	Study of scalability and cost-effectiveness	[Wang et al., 2025]

DISCUSSION

Synthesis and Discussion

The utilization of coal gasification fine slag (CGFS) has been steadily advancing in recent years, as evidenced by the numerous applications that have been explored. From its role in waste-to-energy processes to its use in adsorbent materials for heavy metals, CGFS has moved beyond its status as a mere waste product to become a valuable resource in multiple sectors. Recent advancements have highlighted its multi-functional capabilities, particularly in energy recovery, environmental protection, and the development of innovative composite materials.

Role of CGFS in Waste-to-Energy and Pollution Control

CGFS has shown substantial promise in waste-to-energy applications, particularly when co-combusted with other materials like biomass and sewage sludge. Studies by **Wang et al. (2025)** and **Shi et al. (2025)** show that the co-combustion of CGFS with biomass helps mitigate the environmental impacts of both waste types while enhancing energy production efficiency. Additionally, the high-temperature co-combustion process has proven to reduce emissions such as NO_x and SO_x, which are commonly released during traditional combustion processes.

In environmental pollution control, CGFS has demonstrated exceptional capabilities in

removing heavy metals from industrial effluents. For instance, **Mehmood et al. (2025)** found that CGFS-based adsorbents are highly effective at removing toxic metals like Pb(II) and Hg(II) with over 98% removal efficiency. This makes CGFS a promising material for use in wastewater treatment, where heavy metal contamination is a significant concern.

Development of Advanced Materials with CGFS

One of the most innovative uses of CGFS is its incorporation into advanced materials, particularly in the realm of electromagnetic shielding and thermal management. Research by **Zhang et al. (2025)** demonstrated that CGFS-based composites exhibit excellent electromagnetic interference (EMI) shielding properties, making them suitable for applications in electronics and telecommunications. These composites have shown shielding effectiveness (SE) in the X-band that exceeds commercial standards. Furthermore, CGFS composites also exhibit impressive thermal conductivity, which positions them as potential materials for heat management in electronic devices.

In the construction sector, CGFS has been successfully incorporated into cement-based composites, improving both the mechanical properties and sustainability of construction materials. **Wang et al. (2025)** highlighted that CGFS not only enhances the durability of cement-based materials but also reduces the environmental impact of cement production, which is traditionally associated with high CO₂ emissions. The inclusion of CGFS in cementitious materials offers a viable solution to both solid waste disposal and the sustainability challenges in the construction industry.

Environmental and Health Risks of CGFS

Despite the numerous benefits, the disposal and utilization of CGFS are not without risks. The primary concern remains the leaching of heavy metals and other toxic

components, which can pose significant environmental and health hazards. Studies such as **Xu et al. (2025)** and **Ren et al. (2025)** have explored the leaching behavior of CGFS under different environmental conditions, particularly in acidic media. The results indicate that certain metals, such as Zn, Ni, and Mn, exhibit high mobility and can contaminate groundwater and soil if not properly managed.

To address these concerns, researchers have proposed various stabilization and encapsulation methods, such as embedding CGFS in composite materials or applying surface modifications to reduce the leachability of metals. **Shi et al. (2025)** suggested that the co-combustion of CGFS with sewage sludge could reduce the leaching risk by stabilizing the heavy metals in the ash residue. Additionally, **Guo et al. (2025)** highlighted the potential of CGFS as an adsorbent material for CO₂ capture, further contributing to mitigating environmental risks associated with the material.

Potential for Resource Recovery and Industrial Reuse

One of the most promising aspects of CGFS utilization is its potential for resource recovery, particularly in the context of recycling metals and other valuable components. Research by **Zhang et al. (2025)** and **Wang et al. (2025)** has demonstrated that CGFS can be used as a precursor for the production of high-value materials such as activated carbon and carbon-based adsorbents. These materials can then be employed in various industrial applications, including energy storage, water treatment, and even as electromagnetic shielding materials.

Additionally, the high carbon content in CGFS makes it a suitable candidate for use in the production of biochar, a renewable material with applications in carbon sequestration, soil remediation, and as a substitute for fossil fuels in industrial processes. As **Wang et al. (2025)** discussed, biochar production from CGFS could not

only help in carbon mitigation but also provide an economically viable use for the material.

CONCLUSION

The utilization of coal gasification fine slag (CGFS) has advanced significantly, moving it from a waste product to a valuable resource in multiple industries. From its application in waste-to-energy systems to its incorporation in advanced composite materials and pollution control technologies, CGFS demonstrates a wide array of beneficial uses. However, challenges remain in managing its environmental risks, particularly with regard to the leaching of heavy metals. Future research should focus on improving CGFS stabilization techniques, enhancing its material properties, and exploring new applications in resource recovery.

The ongoing exploration of CGFS's potential in emerging technologies, such as CO₂ capture and biochar production, provides exciting opportunities for advancing sustainability in industrial practices. Moreover, as regulations surrounding waste disposal and pollution control become more stringent, CGFS's role in mitigating environmental impacts and contributing to circular economy practices will likely become more prominent.

In the coming years, it will be crucial to develop scalable solutions for CGFS utilization that address both its environmental benefits and risks. Additionally, advancing the understanding of its interaction mechanisms in co-combustion processes, pollutant adsorption, and material properties will open up new avenues for its widespread adoption

Conclude your research paper here.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

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How to cite this article: Hendri Iyabu, Abdul Haris Panai, Sukirman Rahim, Marini Susanti Hamidun, Weny J.A Musa, Novri Youla Kandowanko et al. Recent advances in coal gasification fine slag utilization: environmental impact, applications, and technological innovations. *International Journal of Research and Review*. 2026; 13(4): 207-213. DOI: <https://doi.org/10.52403/ijrr.20260420>
