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AMMONIA–COAL CO-FIRING: A CRITICAL REVIEW OF TECHNICAL CHALLENGES AND DECARBONIZATION PATHWAYS

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ABSTRACT

The integration of ammonia as a co-firing agent with coal has emerged as a promising strategy to decarbonize existing thermal power generation infrastructure. This critical review synthesizes insights from 190 peer-reviewed studies published between 2022 and 2025, focusing on combustion behaviour, NO_x formation, ammonia slip, and burner design challenges in ammonia–coal co-firing systems. While the potential for CO_2 emissions reduction is evident, unresolved issues particularly related to flame stability, ash behaviour, and limited validation of CFD models pose significant technical barriers. Underexplored areas such as corrosion impacts, retrofit feasibility at high ammonia ratios, and system-level techno-economic readiness are also addressed. This paper aims to map the evolving research landscape and highlight future pathways for advancing low-carbon co-firing technologies.

KEYWORD

Ammonia, coal, co-firing, combustion, NOx emissions, burner design, CFD, retrofitting, ammonia slip, flame stability

INTRODUCTION

The global urgency to reduce greenhouse gas emissions has accelerated research into low-carbon fuels, including green ammonia. Its carbon-free nature and compatibility with existing combustion systems make ammonia an attractive candidate for co-firing with coal in transitional energy systems. However, challenges remain in balancing its combustion characteristics, emission impacts, and system integration—particularly under high ammonia loadings. Recent work emphasizes the integration of CFD modelling with experimental diagnostics to support scalable, retrofit-ready burner designs.

This paper provides a critical review of the current state of ammonia–coal co-firing, synthesizing recent developments, technical bottlenecks, and future opportunities. The scope encompasses combustion performance, NOx mitigation strategies, system design innovations, and techno-economic feasibility. A thematic analysis is presented with focus on unresolved issues related to combustion behaviour, emissions, and burner design offering a forward-looking perspective for research and deployment.

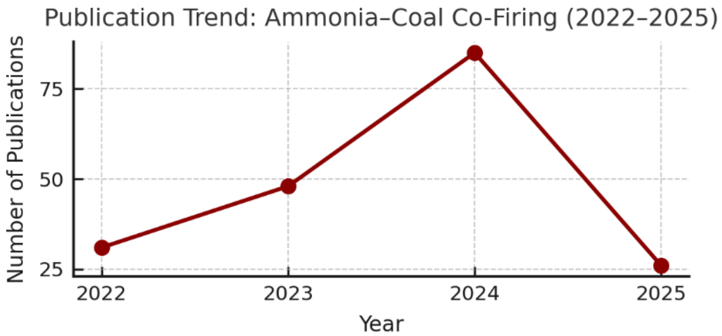

Figure 1: Trend indicates rising research focus on ammonia–coal co-firing, peaking in 2024.

As illustrated in Figure 1, there has been a notable rise in research output since 2022, highlighting intensified interest in ammonia–coal co-firing.

AMMONIA–COAL CO-FIRING TECHNOLOGY OVERVIEW

Ammonia–coal co-firing involves the simultaneous combustion of ammonia and coal within a boiler system, leveraging the existing infrastructure of coal-fired power plants. The primary goal is to reduce carbon dioxide (CO_2) emissions while maintaining operational efficiency. Ammonia contributes no carbon emissions when combusted, but introduces unique challenges due to its high nitrogen content, low reactivity, and combustion instability. Over the past few years, various technological pathways have been explored from direct injection to staged combustion, with varying degrees of ammonia-to-coal energy contribution.

Recent literature has seen a surge in industrial-scale demonstrations and pilot testing. Several studies have evaluated co-firing ratios up to 40%, particularly in drop tube furnaces, 4–50 MWth test rigs, and utility-scale boilers. These trials have provided practical insight into fuel flexibility, retrofit strategies, and environmental trade-offs. Notably, countries such as Japan and Korea have led initiatives integrating ammonia into coal-fired power stations, providing valuable performance data under real-world conditions. These demonstrations commonly employ drop tube furnaces, 50 kW–4 MW pilot rigs, and optical diagnostics such as high-speed imaging and emission spectroscopy to validate combustion trends and emission profiles.

Technological innovations have focused on ammonia injection techniques (axial and tangential), swirl intensity optimization, burner modifications, and combustion air staging to enhance flame stability and reduce NOx. CFD and LES simulations continue to guide design and predict combustion behaviour, but there is an increasing trend of validating simulations with empirical results. Co-firing trials have also begun exploring alternative fuels such as biomass–ammonia blends and hydrogen–ammonia co-utilization, extending the application potential of ammonia beyond coal-only environments.

In summary, the recent trajectory of research has shifted from conceptual modelling to semi-industrial experimentation, signalling a maturation in ammonia–coal co-firing technology development. These advancements help build the foundation for broader deployment in low-carbon energy transition strategies.

RECENT ADVANCES IN AMMONIA CO-FIRING

Ammonia–coal co-firing has seen meaningful progress in recent years, particularly in efforts to overcome key limitations in emissions control, combustion behaviour, and retrofitting strategies. One major development involves the refinement of air staging and flue gas recirculation techniques for suppressing NOx formation. Pilot-scale studies confirm that secondary and tertiary air injections help manage local flame temperatures and reduce the conversion of fuel-N to thermal-NO under moderate co-firing ratios. High-speed optical diagnostics and in-furnace emission probes have been increasingly used in these pilot-scale studies, enabling real-time observation of flame evolution and NOx formation under staged combustion conditions. Strategies to mitigate ammonia slip have also improved. Innovations such as multi-point injection systems, preheated air supply, and staged combustion schemes are being tested to enhance combustion completeness and lower unreacted NH_3 emissions. Coupled CFD–experimental approaches are providing better slip predictions, although full-scale demonstrations remain limited.

Combustion stability enhancements are being pursued through hybrid fuel approaches, particularly the use of ammonia–coal or ammonia–hydrogen blends. These combinations improve ignition delay, flame anchoring, and reduce the risk of flame blow-off in low swirl configurations. Retrofitted swirl burners with optimized vane angles and directional injection have also shown effectiveness in stabilizing ammonia-rich flames. Computational tools such as Large Eddy Simulation (LES) and machine learning-assisted CFD are increasingly applied to predict NOx formation and optimize burner configurations. Despite improvements in turbulence–chemistry interaction modelling, challenges remain in full-scale validation and kinetic simplification.

Recent advances in materials research focus on the evaluation of corrosion-resistant alloys and advanced coatings for their durability in high-ammonia environments. These materials are intended to reduce fouling and extend boiler component life, though most findings are at the lab-scale. Overall, the field has moved from feasibility analysis toward integrated design strategies, reinforcing the technical viability of ammonia–coal co-firing under controlled conditions.

CHALLENGE AND TECHNICAL BARRIERS

Figure 2 summarizes key technical barriers currently hindering the practical deployment of ammonia–coal co-firing systems. Ammonia–coal co-firing technology faces several critical challenges. NOx emission remains the foremost environmental concern, largely driven by ammonia's high nitrogen content and combustion characteristics. Instability in combustion is also a recurring issue, stemming from ammonia's lower reactivity and tendency for longer ignition delay, which can result in unsteady flames and incomplete combustion. High blending ratios often lead to elevated ammonia slip, which presents operational risks and increases the complexity of emission compliance. Furthermore, despite increasing reliance on computational fluid dynamics (CFD) tools for design and diagnostics, many models lack validation against full-scale experimental data, limiting their predictive reliability. Moreover, corrosion behaviour under ammonia-rich environments especially in reducing atmospheres has emerged as a material challenge, with lab-scale findings suggesting the need for advanced coatings or high-performance alloys for boiler tubes. Ash behaviour during ammonia co-firing is not yet fully understood, with varying results on slagging, fouling, and particulate formation, leaving a gap in design considerations for long-term boiler operation. Additionally, concerns related to flame impingement, ammonia infrastructure readiness, and burner retrofitting challenges continue to hinder deployment at scale.

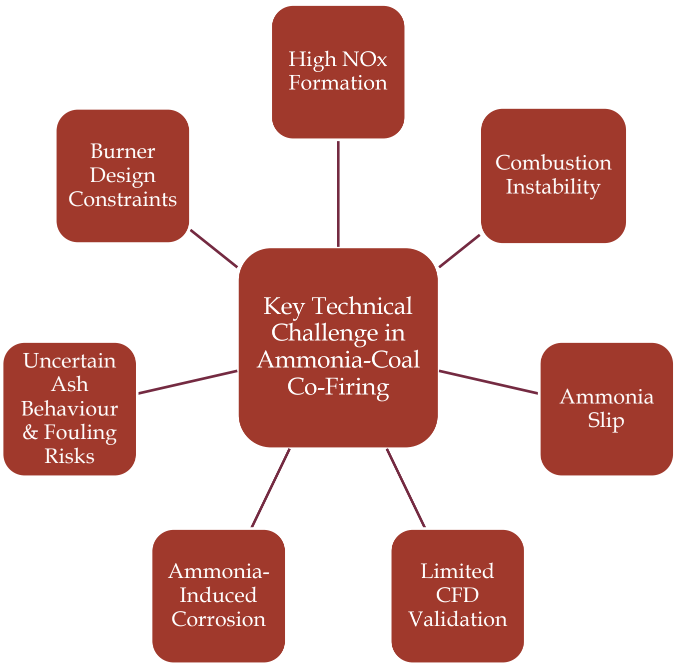

Figure 2: Overview of Technical Barriers in Ammonia–Coal Co-Firing

RESEARCH GAPS AND LIMITATIONS

Despite growing maturity, recent studies reveal persistent knowledge gaps. These include limited full-scale validation of CFD models, lack of visual diagnostics for transient flame structures, and insufficient data on ammonia-coal co-firing in high alkali coals. There is also minimal published work optimizing burner vane angles or NH_3 staging ratios in CFB environments. Addressing these technical gaps will be crucial for enabling practical and scalable deployment.

OUTLOOK AND RESEARCH DIRECTIONS

Ammonia–coal co-firing is advancing from a conceptual strategy to a practical tool in the decarbonization of power generation. Recent innovations in burner geometry, staged injection, and CFD modelling have addressed key combustion challenges and improved operational control. Hybrid blending with hydrogen or biomass offers added potential for stability and reactivity. Nonetheless, core barriers persist. High NOx levels, ammonia slip, and uncertain ash behaviour remain major concerns, especially at higher blending ratios. Additionally, the lack of full-scale validation and the limited availability of retrofit-ready burner designs require immediate attention. Specific gaps also include a lack of optimization studies for ammonia swirl injector geometries, staging ratios, and injection velocity especially within CFB and utility-scale boiler contexts.

Future research must prioritize interdisciplinary approaches—combining combustion science, material development, simulation validation, and techno-economic analysis. Emphasis on full-scale experimental studies and integration-ready technologies will be crucial to translating laboratory success into industrial application. With sustained focus, ammonia–coal co-firing can make a meaningful contribution to reducing emissions in the global power sector.

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