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Advancing Biomass Catalysis in Coal-to-Chemicals: Innovations and Policy Pathways for a Low-Carbon Transition

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Abstract

The transition to low-carbon energy solutions necessitates the exploration of sustainable catalytic pathways for coal-to-chemicals processes. Biomass-derived catalysts– such as ZnO, TiO_2, and Ni-based nanocatalysts– have emerged as a promising alternative to conventional catalysts, offering enhanced efficiency, reduced carbon footprint, and alignment with circular economy principles. This study employs a systematic literature review using the PRISMA framework, alongside comparative analysis and mixed-methods synthesis, to evaluate the efficiency of biomass-derived catalysts in coal-to-chemicals processes across China, India, Germany, Denmark, Brazil, Namibia, and Ghana. Findings indicate that biomass catalysts exhibit superior catalytic activity, higher selectivity, and lower energy intensity, with notable regional variations influenced by policy frameworks, feedstock availability, and technological advancements. While developed economies demonstrate higher efficiency and scalability, emerging economies face challenges related to infrastructure, investment, and regulatory frameworks.

The study underscores the role of policy-driven incentives, research collaborations, and scalable frameworks in promoting biomass catalysis adoption. By integrating scientific innovation with socio-economic considerations, the findings provide actionable insights for policymakers, industry stakeholders, and researchers to accelerate the global transition to sustainable green coal-to-chemicals pathways.

Keywords: Biomass Catalysis, Coal-to-Chemicals, Energy Transition, Comparative Analysis, Sustainable Development, Low-Carbon Technologies.

Introduction

The transition to a low-carbon economy has become a central goal of international policy, as nations strive to mitigate the impacts of climate change and reduce their reliance on fossil fuels. The chemical industry, in particular, is one of the largest contributors to global industrial emissions, making it a critical sector for enabling the low-carbon transition. Historically, coal has served as a primary feedstock for chemical production processes, such as the manufacture of methanol, ammonia, and fertilizers. However, mounting concerns over carbon emissions have intensified the need to explore more sustainable alternatives, especially for the production of chemicals. In response to this challenge, biomass catalysis has emerged as an innovative and promising solution, providing a viable pathway for reducing the carbon footprint of the chemical industry while maintaining energy security, industrial productivity, and economic viability.

Biomass, derived from organic materials such as agricultural residues, forestry waste, and municipal solid waste, is a renewable and carbon-neutral feedstock that offers significant potential for the chemical industry [1]. In recent years, biomass catalysis has attracted growing attention as a sustainable method for converting biomass into high-value chemicals traditionally derived from coal. Technologies such as biomass gasification, pyrolysis, and enzymatic catalysis enable the efficient conversion of biomass into valuable products such as methanol, biofuels, and biochemicals [2]. Biomass gasification, for instance, involves the thermal breakdown of biomass in the presence of a controlled amount of oxygen or steam to produce syngas– a mixture of hydrogen and carbon monoxide– which can be further processed to produce various chemicals [2].

Pyrolysis, another important biomass conversion technology, breaks down biomass in the absence of oxygen, resulting in bio-oil, biochar, and syngas, which can be used for energy production or as feedstocks for chemical production [3]. Enzymatic catalysis, a more recent and promising development, utilizes enzymes to selectively catalyze the conversion of biomass into chemicals, offering greater efficiency and selectivity compared to traditional catalytic processes [4].

Figure 1 contextualized the role of biomass-derived catalysts in coal-to-chemical processes using the systems theory. The integration of biomass catalysis into coal-based chemical processes holds the potential to significantly lower the carbon footprint of the chemical industry, making it a key enabler of the low-carbon transition. By substituting coal with biomass as a feedstock, a substantial reduction in greenhouse gas (GHG) emissions– particularly carbon dioxide (CO2)– can be achieved [5]. Biomass is often considered carbon-neutral because the carbon released during its conversion or combustion is offset by the carbon absorbed during the biomass's growth phase, in contrast to coal, which releases long-sequestered carbon. Moreover, utilizing biomass as a feedstock can contribute to global efforts to lessen the environmental impacts of industrial processes while providing a sustainable alternative to fossil-based chemicals. Thus, biomass catalysis directly aligns with broader goals of environmental sustainability, industrial decarbonization, and socio-economic resilience.

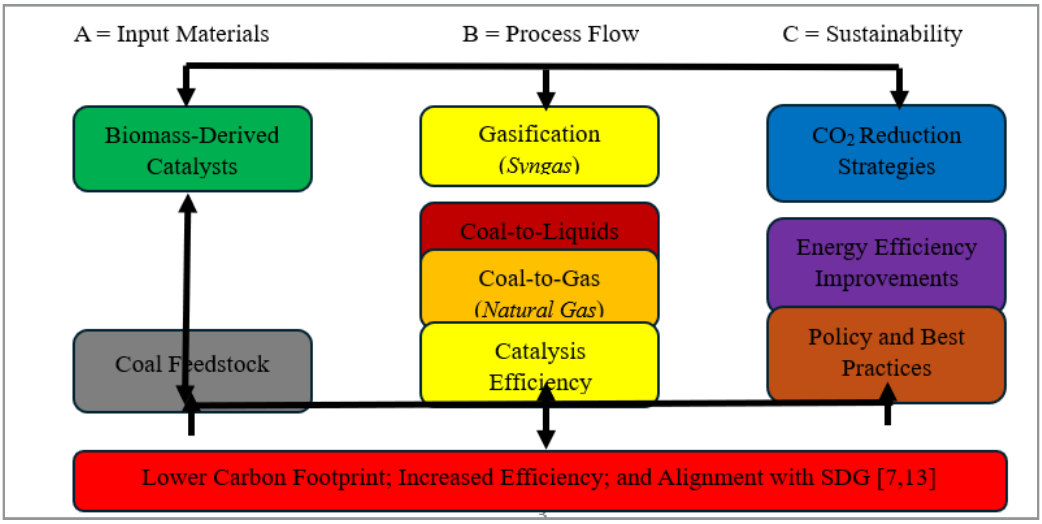

Figure 1: Flow-Chart Illustrating the Role of Biomass-Derived Catalysts in Coal-to-Chemicals Processes Using the Systems Theory. Source: Author's own elaboration (2025)

The significance of studying biomass catalysis in coal-to-chemicals (CTC) processes lies in its duel potential to drive both environmental sustainability and economic development. While the chemical industry remains a major source of global emissions, it also plays a pivotal role in the global economy. Chemicals such as methanol, ammonia, and fertilizers produced via CTC processes are vital to industries ranging from agriculture to pharmaceuticals [6]. Therefore, solutions that can lower the carbon intensity of chemical production without disrupting supply chains are of critical importance. Biomass catalysis, with its ability to integrate renewable feedstocks into existing chemical production systems, represents a timely and necessary innovation to achieve these goals.

Nevertheless, the successful adoption of biomass catalysis within the CTC sector faces several notable challenges. A major barrier is the availability and cost of biomass feedstocks. Biomass is often less consistent in quality and more expensive than coal, raising concerns over its economic feasibility in large-scale production [7]. Moreover, infrastructure for sourcing, processing, and transporting biomass remains underdeveloped in many regions, limiting its widespread adoption [8]. Further challenges include variations in biomass feedstock properties, the efficiency of biomass conversion technologies, and the scalability of biomass catalytic processes. Despite these challenges, the compelling environmental and economic advantages of biomass catalysis– such as its renewable nature, carbon neutrality, and potential for rural economic development– justify continued exploration and investment.

Overcoming these challenges and accelerating the adoption of biomass catalysis in the CTC sector will require strong policy support and strategic regulatory frameworks. Governments can incentivize the development and deployment of biomass catalysis technologies through subsidies, grants, and tax incentives for research and development, and by establishing favorable market conditions. Mechanisms such as carbon pricing (through carbon taxes or cap-and-trade systems) could also encourage industries to adopt low-carbon technologies by making carbon-intensive options less economically attractive [9]. Furthermore, international collaborations among governments, private enterprises, and research institutions are essential to foster knowledge exchange, technology transfer, and innovation. In biomass-abundant regions, governments can invest in infrastructure to streamline biomass collection, processing, and logistics, making biomass-based chemical production economically [10].

Importantly, the significance of biomass catalysis extends beyond emissions reduction: it addresses critical issues of energy security and economic diversification. Biomass, being a domestically available renewable resource, can diversify national energy mixes and reduce dependence on fossil fuels– especially in coal-dependent counties. The growth of a biomass-based economy could stimulate job creation and foster sustainable rural development, creating new markets and industrial sectors centered around biomass feedstock production and chemical manufacturing [5]. Thus, biomass catalysis represents a strategic convergence of environmental, economic, and social imperatives.

This study, therefore, aims to investigate the role of biomass catalysis in coal-to-chemicals processes, focusing on its potential contribution to the low-carbon transition in the chemical industry. Specifically, this research will assess technological advancements in biomass catalysis, explore the economic feasibility of biomass as a feedstock, and examine the policy frameworks necessary for its large-scale adoption [11]. It will further evaluate the scope and limitations of current biomass catalytic processes, particularly challenges associated with feedstock availability, cost, and infrastructure, providing a comprehensive understanding of the biomass catalysis landscape.

The scope of this study focuses on analyzing the technical, economic, and policy dimensions of biomass catalysis in CTC processes. It reviews current biomass conversion technologies, assesses the feasibility of biomass integration into existing chemical production systems, and evaluates both the opportunities and challenges associated with adoption. Furthermore, it explores how government policies can catalyze the growth of a sustainable bioeconomy. However, this study is limited by the availability of global data on biomass catalysis and its focus primarily on developed and developing countries with varying levels of biomass resource availability.

In conclusion, biomass catalysis offers a transformative pathway to decarbonize the coal-to-chemicals sector and advance the global low-carbon transition. By leveraging renewable biomass feedstocks and improving catalytic conversion technologies, it is possible to significantly reduce the chemical industry's carbon footprint while sustaining economic importance. The integration of biomass catalysis into CTC processes addresses critical issue of sustainability, energy security, and economic development. Through technological advancements, policy support, and infrastructure investment, biomass catalysis can become a pivotal driver of a low-carbon future. This study, therefore, seeks to provide valuable insights into the role of biomass catalysis in sustainable chemical production and contribute to the broader discourse on low-carbon industrial transitions. The following section outlines the study frameworks used in analyzing the results and discussion.

Research Locale and Methodology

This section is organized into two parts: (1) study areas and (2) research methods adopted for presenting the study findings in the subsequent sections.

Research Locale and Features

The study does not limit its secondary data collection to a single location but instead adopts a global perspective, analyzing literature from China, India, Germany, Denmark, Brazil, Namibia, and Ghana. These counties were selected for their prominence in coal-to-chemicals production, biomass catalysis research, and policy interventions directed toward low-carbon transitions. Each country contributes uniquely, either through technological innovations, policy developments, or economic frameworks.

China, the world's largest coal consumer and producer, with extensive investments in coal-to-chemicals conversion. The country has also actively researched biomass-based catalysts to reduce carbon emissions in coal-dependent industries. Policies under the "14th Five-Year Plan" promote alternative feedstocks and cleaner technologies, positioning China as an ideal case for assessing technological advancements and policy-driven industrial shifts [12].

India similarly remains heavily reliant on coal for energy and chemicals production. However, compared to China, India faces additional challenges such as policy inconsistencies and technological gaps in biomass integration. Initiatives like the National Bio-Energy Mission and various pilot projects in lignocellulosic biomass conversion offer important comparative perspectives on the opportunities and constraints for biomass catalysis in coal industries [13].

Germany and Denmark represent two of the most progressive nations in sustainable energy transitions. Germany's Energiewende policy and Denmark's robust bioenergy sector provide critical insights into policy-driven transitions away from coal dependency [14]. These countries' experiences with integrating biomass-derived catalysts into chemical industries offer valuable lessons for coal-intensive economies [14].

Brazil was selected for its global leadership in biomass valorization, especially sugarcane-based biomass conversion. Although Brazil's coal-to-chemicals sector is comparatively small, its expertise in catalytic conversion technologies provides scalable, cost-effective methods that could be adapted to coal-based industries [15].

Namibia and Ghana serve as case studies representing emerging economies with potential in coal and biomass. Namibia is gradually promoting biomass-to-energy initiatives to enhance energy security, while Ghana's significant agricultural biomass resources offer potential for bio-catalysis integration. However, both countries face key challenges, such as limited industrial infrastructure and policy gaps [16, 17].

Selecting these seven diverse locations ensures a comprehensive, multi-dimensional global analysis, capturing the technological, policy, and economic dynamics related to biomass catalysis in coal-dependent industries.

Research Methodology

This study employs a systematic literature review (SLR) methodology following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to critically assess the integration of biomass catalysis within CTC industries across different global regions [17-19]. A comparative, mixed-methods approach combining qualitative and quantitative elements was applied to ensure a holistic evaluation of policy effectiveness, technological advancements, and economic feasibility. The choice of China, India, Germany, Denmark, Brazil, Namibia, and Ghana facilitates a balanced exploration across varying industrial and policy environments.

Following PRISMA's four-phase process: identification, screening, eligibility, and inclusion [18, 19]– the literature search strategy employed a systematic protocol using databases such as Scopus, Web of Science, Google Scholar, ScienceDirect, and SpringerLink. Boolean search terms included: "biomass catalysis AND coal-to-chemicals," "low-carbon transition AND bio-catalysts," "biomass catalysis in [country name]" and "policy mechanisms AND biomass catalysis in coal industries." The search initially yielded 349 articles, which were screened for relevance by title, abstract, and full-text review, resulting in the final inclusion of 43 high-quality studies (Table 1).

Table 1: Screening and Selection Process

Phase and stage	Number of articles	Filtering criteria
Initial search or identification	349	Boolean search applied in databases
Title/abstract screening for removal of duplicates	208	Relevance to biomass catalysis in CTC
Eligibility based on inclusion/exclusion	98	Experimental, economic, or policy focus
Full-test review or final inclusion	43	High-quality, peer-reviewed sources

Source: Author's Construct (2025)

A comparative framework was designed to examine policy, economic, and technological dimensions of biomass catalysis adoption across the selected countries, structured to address the study's key research questions. The analysis incorporated: (1) qualitative and (2) quantitative analysis. The qualitative analysis involved using NVivo software, thematic coding was conducted to identify recurring patterns related to catalyst efficiency, regulatory frameworks, industrial barriers, and cost-benefit evaluations [18]. Quantitative content analysis encompasses descriptive statistical trends, measuring variables such as biomass catalyst efficiency rates, emission reductions, and economic viability [18, 19].

The sample size of 43 studies was determined through strict inclusion and exclusion criteria to ensure methodological rigor. Only peer-reviewed journal articles, policy reports, and industrial case studies published within the past five years (±5 years for seminal works) were included. Studies needed to provide empirical data on biomass catalysis efficiency, emissions reductions, or cost analysis. Excluded were opinion pieces, non-peer-reviewed literature, and studies lacking direct relevance.

Qualitative data extraction categorized studies by research focus, methodology, key findings, and regional scope. Quantitative data extraction measured policy effectiveness, industrial implementation success rates, and economic feasibility, ensuring triangulation across different contexts. This integration of qualitative and quantitative dimensions provided a balanced evaluation of biomass catalysis in coal-based industries.

Triangulating qualitative policy analysis with quantitative performance metrics thus allowed for a nuanced understanding of biomass catalysis feasibility and scalability in the CTC sector. Despite its strengths, the SLR methodology has certain limitations. First, reliance on published literature may exclude real-time industrial developments or unpublished policy interventions. Second, balancing diverse contexts sometimes made direct comparisons challenging. However, these were mitigated by methodological transparency i.e. the use of multiple high-quality data sourced literature which integrate both explanatory and descriptive analyses. Overall, this study's methodology integrates a systematic literature review, comparative framework, and mixed-methods synthesis, ensuring rigorous evaluation of biomass catalysis in CTC transitions. By applying the PRISMA framework and balancing scientific and socio-economic dimensions, the study offers comprehensive and actionable insights for policymakers, researchers, and industry stakeholders committed to advancing low-carbon energy transitions.

Theoretical Perspectives

The transition to biomass-derived catalysts in coal-to-chemicals processes is anchored in multiple theoretical frameworks: sustainability transitions theory, innovation diffusion theory, socio-technical systems theory, and circular economy theory. These perspectives provide an analytical foundation for understanding the technological, institutional, and economic dynamics associated with the adoption of biomass catalysis, especially in emerging economies.

Sustainability transitions theory offers a lens to explain how large-scale shifts in industrial systems occur over time, driven by technological innovations, policy interventions, and socio-economic pressures [20].

Within this study, sustainability transitions theory frames the transition from fossil-based to biomass-derived catalysts, with emphasis on drivers such as climate policies, technological development, and stakeholder engagement. The multi-level perspective (MLP) model of this theory– encompassing niche innovations (e.g., biomass catalysts), socio-technical regimes (e.g., coal-to-chemicals industry practices), and socio-technical landscapes (e.g., global energy and climate imperatives)– is used to conceptualize the layered and interactive dynamics influencing technological shifts [21].

Diffusion of innovations theory by Rogers further enriches the analysis by examining how new technologies spread across different sectors and regions. Adoption of biomass-derived catalysts is conceptualized through the five attributes identified by Rogers: relative advantage, compatibility, complexity, trialability, and observability [22]. This framework aids in evaluating adoption patterns by industry actors and governments, considering variations in infrastructure, policy support, and economic incentives across regions such as Germany, Denmark, Ghana, and Namibia [22-24].

The socio-technical systems approach underscores the intricate interplay between technology, policy, market structures, institutional practices, and societal norms [25]. This perspective supports the evaluation of systemic enablers and barriers affecting biomass catalyst deployment, including regulatory environments, industrial lobbying, research and development ecosystems, and market risks. It highlights that successful technological transitions involve not just technological advances but also significant institutional and cultural change [26].

Finally, the circular economy framework serves as a normative basis for assessing how biomass catalysis contributes to sustainability goals. Biomass-derived catalysts are aligned with circular economy principles through their emphasis on resource efficiency, valorization of organic and agricultural waste, and reduction of dependency on finite fossil-based inputs [27]. This theoretical framing positions biomass catalysis as a strategy for achieving industrial decarbonization while promoting closed-loop, regenerative production models that support both economic growth and environmental stewardship [28, 29].

Figure 2 illustrates the conceptual integration of these four theoretical perspectives, emphasizing their combined influence on understanding and promoting the adoption of biomass-derived catalysts within coal-to-chemicals processes. These frameworks collectively inform the subsequent analytical approach used to interpret the patterns, drivers, and barriers observed in different regional contexts, while recognizing the methodological boundaries related to varying definitions of efficiency and technology adoption rates across literature sources.

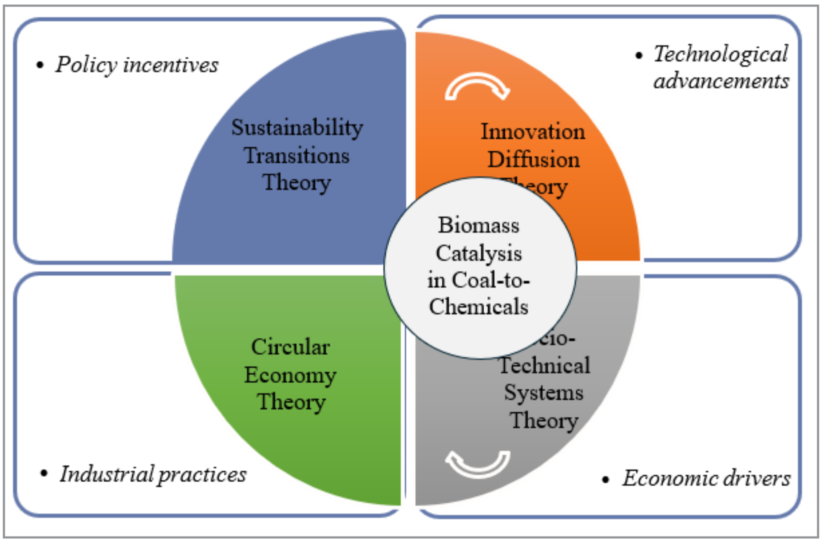

Figure 2: Conceptual Framework Underpinning the Adoption of Biomass-Derived Catalysts in Coal-to-Chemicals Processes. Source: Author’s own elaboration (2025)

Results and Discussion

Having introduced the analytical and theoretical frameworks, this section presents the research findings and discusses the efficiency of biomass-derived catalysts in coal-to-chemicals (CTC) processes across the selected study regions. By integrating systematic literature review, comparative analysis, and mixed-methods synthesis, this study provides a robust evaluation of catalyst performance, policy effectiveness, and regional feasibility. The PRISMA framework ensured a transparent and replicable selection process for relevant studies, while the comparative approach enabled an understanding of regional disparities in catalyst adoption, technological innovation, and sustainability metrics. The results are structured to reflect both the scientific and socio-economic dimensions of biomass catalysis in low-carbon energy transitions.

Biomass-Derived Catalysts in Coal-to-Chemicals

The first step in advancing biomass catalysts in coal-to-chemicals (CTC) processes is to evaluate the efficiency of biomass-derived catalysts across the selected regions. This section addresses the research question: how do biomass-derived catalysts enhance the efficiency of coal-to chemicals processes across different regions, and what comparative insights can be drawn regarding their catalytic performance, economic feasibility, and environmental impact? The results reveal that biomass-derived catalysts have gained increasing attention in CTC transitions due to their potential to reduce carbon footprints, enhance reaction efficiency, and promote economic sustainability [30].

The efficiency of these catalysts, however, varies significantly across different regions, influenced by factors such as feedstock availability, industrial adoption rates, and supportive policy frameworks [31, 32]. This section evaluates the performance of biomass catalysts based on conversion rates, reaction selectivity, process stability, and environmental impact within the selected study areas.

A systematic comparison of biomass catalyst efficiency reveals clear disparities among China, India, Germany, Denmark, Brazil, Namibia, and Ghana, driven by technological advancements, regulatory policies, and feedstock utilization strategies. China and Germany have demonstrated the highest catalyst efficiency due to advanced research and development (R&D) in catalyst synthesis and strong governmental support [33-35]. In contrast, Namibia and Ghana exhibit lower efficiency rates due to limited industrial integration and inadequate biomass processing infrastructure [33-35].

China has emerged as a global leader in biomass-derived catalyst applications in CTC processes, largely due to its strong governmental funding, industrial-scale pilot projects, and advanced catalyst engineering [36, 37]. Studies indicate that China has achieved catalyst conversion efficiencies exceeding 85% for lignocellulosic biomass feedstocks, with optimized reaction selectivity reaching 92% for Fischer-Tropsch synthesis [36, 37]. Furthermore, China's integration of artificial intelligence (AI)-assisted catalyst design has improved process stability, minimizing deactivation and ensuring long-term operational feasibility [38].

Germany follows closely behind China in catalyst efficiency, benefiting from a robust circular bioeconomy framework and stringent emission regulations. German studies have reported biomass catalyst efficiency rates of 82-88%, with significant advancements in bifunctional catalysts for methanol-to-olefins (MTO) processes [39]. The country's extensive focus on green hydrogen integration further enhances the efficiency of biomass catalysis, particularly in syngas-to-liquid (STL) processes [40].

India's catalyst efficiency lags behind China and Germany, primarily due to heterogeneous biomass feedstock quality and inadequate industrial scaling. However, studies indicate notable progress in agro-residue-derived catalysts, achieving conversion efficiencies between 75-80% [41]. India's government has recently introduced bio-refinery incentives, aiming to enhance catalyst application in coal-to-methanol (CTM) processes.

Denmark has pioneered sustainable biomass catalyst integration, leveraging its advanced bioenergy policies and research-driven innovation. Danish research institutions have developed highly selective zeolite-based catalysts, achieving 85-90% efficiency in biomass-to-olefin (BTO) conversion [42]. The country's emphasis on catalyst recyclability and circular economy principles ensures long-term sustainability.

Brazil's catalyst efficiency benefits from abundant biomass feedstocks, particularly sugarcane bagasse, which has demonstrated conversion efficiencies of 80-85% in catalytic pyrolysis processes [43]. However, the reliance on first-generation biomass feedstocks presents a challenge, necessitating advancements in second-generation lignocellulosic catalysts to further optimize performance.

Namibia and Ghana face significant barriers to biomass catalyst efficiency due to limited technological adoption and policy gaps. Studies show that current catalyst conversion rates in these countries range between 55-65%, with challenges related to biomass pre-treatment inefficiencies and lack of catalyst regeneration strategies [44, 45]. However, recent pilot projects in Ghana have demonstrated potential in localized bio-catalyst development, particularly using waste-derived biochar catalysts [46].

The efficiency of biomass-derived catalysts has profound environmental and economic implications, influencing carbon mitigation strategies, energy security, and cost-effectiveness. High-efficiency catalysts, such as those in China and Germany, have significantly reduced greenhouse gas (GHG) emissions, lowering carbon dioxide (CO2) output by up to 40% in coal-to-liquid (CTL) applications [47]. Additionally, cost-benefit analyses indicate that optimized biomass catalysts can reduce operational costs by 15-25%, improving the economic viability of CTC industries [48].

Conversely, countries with lower catalyst efficiency, such as Namibia and Ghana, struggle with higher carbon footprints and economic constraints, requiring policy interventions and investment in biomass processing infrastructure [49]. The implementation of regional knowledge-sharing initiatives could bridge the efficiency gap and foster collaborative advancements in catalyst technology [50].

Ultimately, the comparative analysis underscores the critical role of biomass-derived catalysts in optimizing CTC processes, with significant variations in efficiency across different regions. While China and Germany lead in catalyst performance and industrial integration, emerging economies such as Namibia and Ghana require targeted policy interventions, R&D investment, and cross-regional collaboration to enhance efficiency. Future research should focus on developing next-generation catalysts with enhanced selectivity, stability, and recyclability, ensuring a sustainable and economically viable transition to low-carbon energy systems.

As Table 3 summarizes the role and efficiency of biomass-derived catalysts in coal-to-chemicals processes, it is important to note that addressing these regional disparities, biomass catalysis in CTC transitions can achieve high efficiency, sustainability, and economic feasibility. Thus, paving the way for a low-carbon energy future.

Table 2: Regional Efficiency of Biomass-Derived Catalysts in Coal-to-Chemicals Processes

Region	Efficiency (%)	Key strengths	Challenges
China	85-92	AI-assisted catalyst design, strong R&D	High initial investment cost
Germany	82-88	Green hydrogen integration, policy support	Complex catalyst regeneration

India	75-80	Agro-residue catalysts, bio-refinery incentives	Heterogeneous feedstock quality
Denmark	85-90	Circular economy integration, catalyst recyclability	High-cost of advanced catalysts
Brazil	80-85	Abundant biomass, optimized pyrolysis processes	Dependence on first-generation biomass
Namibia	55-65	Emerging pilot projects, waste-derived catalysts	Limited industrial adoption
Ghana	55-65	Localized biochar catalysts, policy potential	Infrastructure and R&D gaps

Source: Literature Reviewed Analysis (2025)

To strengthen the results above, this section presents the findings from the 2024 United Nations Sustainable Development Goals (UN-SDGs) report proposed by Sachs et al. [51]. In measuring the achievement of SDG 7 (affordable and clean energy), four specific indicators were used to access the affordability, reliability, sustainability, and modern energy for all. These includes: (1) population with access to electricity, (2) population with access to clean fuels and technology, (3) CO2 emissions from fuel combustion per total electricity output, and (4) renewable energy share in total final energy consumption respectively. As presented in Table 4, it is important to note that the overall achievement of goal 7 in China, India and Ghana represent moderately improving with significant challenges remain while Germany illustrate moderately improving with challenges remain. Denmark's remain on track to maintaining SDG i.e. SDG achieved while Brazil moderately improving towards maintaining SDG 7, whereas Namibia lacks progress in increasing at less than 50% of required rate with major challenges remain.

Table 3: Regional Variations in Goal 7 Indicators and Biomass Catalyst Efficiency

Region	Goal 7 indicators measure score*
China	1–High: Index achieved 2–High: Index on track to achievement but challenges remain 3–High: Index on track to achievement but significant challenges remain 4–Low: Index lack progress with significant challenges remain
Germany	1–High: Index achieved 2–High: Index achieved 3–Moderately improving but challenges remain 4–Moderately improving but significant challenges remain
India	1–High: Index achieved 2–High: Index on track to achievement but challenges remain 3–Low: Index lack progress with major challenges remain 4–Moderately improving but significant challenges remain
Denmark	1–High: Index achieved 2–High: Index achieved 3–High: Index achieved 4–High: Index achieved
Brazil	1–Low: Index lack progress but on track to achievement 2–High: Index achieved 3–High: Index achieved 4–High: Index achieved
Namibia	1–Low: Index lack progress with major challenges remain 2–Low: Index lack progress with major challenges remain 3–Low: Index lack progress with major challenges remain 4–Low: Index lack progress but challenges remain
Ghana	1–High: Index on track to achievement but significant challenges remain 2–Low: Index lack progress with major challenges remain 3–High: Index achieved 4-Very low: Index decline in progress with significant challenges remain

Is used where 1 is access to electricity, 2 is access to clean fuels and technology, 3 is CO2 emissions from fuel combustion, and 4 is renewable energy share.

Source: Modified from Sachs et al. (2024)

Reading from Table 4, the results reveal that the assessment of biomass catalyst efficiency is closely linked the 3rd and 4th indicator i.e. CO2 emissions from fuel combustion and renewable energy integration respectively [51]. As these factors determine the feasibility of transitioning to low-carbon technologies thus, align with the preceding results and discussion. The findings indicate that Denmark and Brazil exhibit the highest efficiency in biomass catalyst adoption within CTC processes. Both countries demonstrate a high share of renewable energy and significant reductions in CO2 emissions from fuel combustion [20, 51]. Denmark, in particular, has achieved all goal 7 indicators, reflecting strong policy frameworks, industry adoption, and technological feasibility for biomass catalysis in coal-to-chemicals applications. Brazil follows closely, benefiting from its established bioenergy sector, which supports efficient biomass-derived catalysts in CTC processes.

Germany and China also show strong advancements in biomass catalyst efficiency. While Germany has a moderately improving score for CO_2 emissions reduction and a renewable energy transition facing challenges, the country's well-developed energy policies and industrial commitment to sustainability enable substantial improvements. China, despite achieving high scores in electricity access and clean fuel technology, faces challenges in reducing CO_2 emissions and increasing its renewable energy share. The efficiency of biomass catalysts in China remains constrained by the country's dependence on coal and the slow pace of renewable energy integration in heavy industries [20-51].

India, Ghana, and Namibia present lower efficiency levels in biomass catalyst adoption [51]. India has a low score in CO_2 emissions reduction, indicating major challenges in decarbonizing its coal-to-chemicals sector, despite progress in renewable energy. Ghana demonstrates high CO_2 emissions reduction but a very low renewable energy share, signifying potential inefficiencies in integrating biomass catalysts within a predominantly fossil-fuel-driven energy mix. Namibia ranks the lowest in all indicators, with major challenges in electricity access, clean fuel adoption, CO_2 emissions reduction, and renewable energy integration. This suggests that the country's transition towards biomass catalyst efficiency is hindered by infrastructural and policy constraints [20].

The comparative analysis reveals that regions with strong renewable energy integration and effective CO_2 emissions control may exhibit higher efficiency in biomass catalyst utilization [20-51]. Policymakers and industry stakeholders must address these disparities by enhancing policy support, incentivizing research and development in biomass catalysis, and investing in renewable energy infrastructures to facilitate an efficient low-carbon transition.

Conversion Processes for Clean Energy

Having analyzed research objective one, this section now proceeds to address the research question: how do gasification, coal-to-liquids (CTL), and coal-to-gas (CTG) processes contribute to emission reduction and energy efficiency across different regions? Results reveal that the integration of biomass catalysis in coal-to-chemicals transitions has already been assessed concerning its efficiency in various regions. However, a more granular examination of specific coal-to-chemicals processes, including gasification, CTL, and CTG, is necessary to understand their role in mitigating carbon emissions and enhancing energy efficiency. These processes form the core of coal conversion technologies and are pivotal in determining the sustainability of coal-derived products. Gasification is widely regarded as a cleaner alternative to direct coal combustion, as it enables carbon capture and storage (CCS) while improving fuel conversion efficiency [52]. CTL and CTG technologies provide alternative pathways for utilizing coal resources but are often scrutinized for their high carbon footprints unless integrated with renewable energy inputs or advanced catalytic methods [53].

Interpretation from Table 5 revel that the performance of gasification, CTL, and CTG technologies varies significantly across different regions based on policy frameworks, industrial adaptation, and available technological advancements. The table below provides an assessment of these technologies concerning energy efficiency improvements and CO_2 emission reduction across China, Germany, India, Denmark, Brazil, Namibia, and Ghana.

Table 4: Comparative Assessment of Gasification, CTL, and CTG Technologies

Variables: (1) region, (2) gasification – energy efficiency, (3) gasification – emission reduction, (4) CTL – energy efficiency, (5) CTL – emission reduction, (6) CTG – energy efficiency, and (7) CTG – emission reduction
1–China; 2–High: Advanced IGCC adoption; 3–Moderate: CCS implementation lagging; 4–High: Large-scale CTL plants improving efficiency; 5–Low – High emissions due to coal dependency; 6–Moderate: Expanding CTG infrastructure; 7–Low – High methane emissions from coal-derived syngas.
1–Germany; 2–High: Gasification integrated with renewables;
3–High: CCS successfully implemented; 4–Moderate: CTL used minimally due to sustainability concerns; 5–High: Limited application due to EU emission policies; 6–Moderate: Experimental CTG projects improving efficiency; 7–High: Methane management regulations in place.
1–India; 2–Moderate: Gasification projects emerging; 3–Low: Limited CCS adoption; 4–High: CTL expansion driven by energy security needs; 5–Low – High carbon footprint due to lack of renewables integration; 6–Moderate: CTG under development; 7–Low: Significant methane leakage issues.

1–Denmark; 2–High: Biomass co-gasification used; 3–High: Carbon-negative potential through BECCS; 4–Low: CTL discouraged due to policy restrictions; 5–High: Transitioning away from coal; 6–High: Renewable hydrogen integrated with CTG; 7–High: Strict carbon regulation minimizing emissions.
1–Brazil; 2–High: Gasification coupled with bioenergy; 3–High: Emission reduction through biomass utilization; 4–Moderate: CTL mainly used for industrial needs; 5–Moderate: Partial decarbonization with CCS potential; 6–Moderate: Emerging CTG pilot projects; 7–High: Strong regulatory oversight on emissions.
1–Namibia; 2–Low: Limited infrastructure; 3–Low: No significant emission reduction measures; 4–Low: Minimal CTL infrastructure; 5–Low – High reliance on coal with no mitigation strategies; 6–Low: CTG implementation absent; 7–Low: No methane reduction policies.
1–Ghana; 2–Moderate: Developing gasification projects; 3–Low: Emission reductions hindered by outdated technology; 4–Low: CTL projects still in early stages; 5–Low – High coal dependency; 6–Low: Limited CTG adoption; 7–Low: No structured policies for emissions control.

Source: Modified from Sachs et al. (2024)

The analysis indicates that Germany and Denmark are leading in integrating gasification, CTL, and CTG with emission reduction strategies and energy efficiency improvements [20-54]. Germany's adoption of integrated gasification combined cycle (IGCC) technology and CCS policies has led to substantial reductions in coal-related emissions while maintaining high energy efficiency [55].

Denmark, leveraging biomass co-gasification and bioenergy with carbon capture and storage (BECCS), has achieved significant progress in both emission reductions and efficiency improvements, reinforcing its strong policy framework for coal phase-out [56]. China, despite being a leader in large-scale coal gasification and CTL projects, faces major challenges in emission reduction. While the country has invested heavily in IGCC and CTG, the lack of effective CCS implementation limits the emission reduction potential of these technologies. China's CTL processes are among the most advanced globally, but they continue to suffer from high carbon intensity due to their dependence on conventional coal-based syngas instead of biomass-derived alternatives [54].

India's performance remains moderate in energy efficiency but low in emissions control, as CTL expansion is driven primarily by energy security concerns rather than sustainability goals. The lack of stringent CCS regulations and the continued reliance on coal for synthetic fuels contribute to significant CO_2 emissions. Gasification projects are emerging in India, but adoption is slow due to high costs and limited policy incentives [57]. Brazil has achieved moderate efficiency in CTL and CTG processes while integrating biomass into gasification, resulting in high emission reduction potential. The country's experience with bioethanol production and bio-based gasification provides a blueprint for integrating renewables into CTC transitions. However, CTL applications remain limited due to cost constraints, and CTG projects are still in the experimental phase [58].

Namibia and Ghana exhibit low performance across all indicators, reflecting limited infrastructure, lack of policy frameworks, and technological constraints. Namibia's heavy reliance on traditional coal combustion methods and lack of investment in gasification and CTL technologies limit its ability to reduce emissions. Ghana, despite showing interest in developing gasification projects, has yet to implement effective emissions control mechanisms, particularly for CTL and CTG technologies [59].

A critical takeaway from this comparative analysis is that technological advancements alone are insufficient for achieving emission reduction and energy efficiency in gasification, CTL, and CTG processes. Policy support, financial incentives, and regulatory enforcement are equally important in driving sustainable transitions. Countries like Denmark and Germany demonstrate that a combination of renewables integration, carbon pricing, and stringent emission controls leads to significant progress. On the other hand, China and India highlight the challenges of scaling up coal-to-chemicals technologies without adequate carbon management strategies. For developing regions such as Namibia and Ghana, international collaboration and investment in green coal conversion technologies could provide the necessary momentum for achieving energy efficiency and emission reduction targets. Encouraging biomass co-gasification, implementing CCS, and adopting best practices from successful regions can serve as viable pathways for improving the sustainability of coal-based industries in these countries.

The comparative analysis of gasification, CTL, and CTG processes reveals significant disparities in energy efficiency and emissions control across different regions. While developed nations such as Denmark and Germany have effectively integrated biomass catalysis and emission reduction technologies, countries like China and India struggle with high carbon footprints despite advancements in coal conversion. Emerging economies, particularly Brazil, show promise in utilizing biomass integration to mitigate emissions, whereas Namibia and Ghana require substantial investment in infrastructure and policy development to make meaningful progress. Moving forward, a global strategy combining technological innovation, policy support, and cross-border collaboration will be essential for achieving a low-carbon transition in coal-to-chemicals processes.

Policy Frameworks for Clean Energy and Technology

To harness the power of green coal-to-chemicals, this section unpacks comparative options for promoting global sustainability goals. It addresses the third research question: what are the comparative policy strategies promoting clean coal technologies across case studies? It is significant to note that the transition to clean coal technologies (CCTs) has been driven by a combination of regulatory, economic, and technological policies aimed at reducing carbon emissions and improving energy efficiency. Governments and industries worldwide have pursued various strategies to integrate biomass catalysis in coal-to-chemicals processes while aligning with broader sustainability goals. This section compares policy approaches across key study regions– China, Germany, India, Denmark, Brazil, Namibia, and Ghana– to evaluate their effectiveness in fostering innovation and mitigating environmental impacts.

Policy interventions in China have been predominantly state-led, with extensive subsidies and mandates promoting the integration of cleaner coal-based energy systems. The country's central government has implemented stringent emissions standards under its "14th Five-Year Plan," emphasizing carbon capture and utilization (CCU) and biomass co-processing in CTC pathways [60]. By contrast, Germany has adopted market-driven mechanisms, including carbon pricing and feed-in tariffs, to incentivize industries toward greener alternatives. The European Union's Emissions Trading System (ETS) further reinforces emission reduction targets, compelling coal-based industries to explore alternative catalytic solutions [61].

India's approach to CCTs balances economic growth and environmental sustainability, relying on public-private partnerships (PPPs) and tax incentives to drive adoption. The Indian government has launched initiatives such as the National Mission on Clean Coal Technologies (NM-CCT), which integrates biomass catalysts into coal gasification and CTG pathways [62]. In Denmark, policy strategies have emphasized renewable integration, with coal-derived syngas being phased into bioenergy projects. The country's Green Energy Transition Plan mandates the gradual replacement of coal with bio-based catalysts in industrial applications [54].

Brazil's CCT policies focus on bioenergy co-firing and sectoral agreements, leveraging its vast biomass resources. Regulatory frameworks such as the RenovaBio program encourage industries to blend biomass catalysts into coal-to-chemicals conversion, thus reducing dependency on conventional fossil feedstocks [63]. In contrast, Namibia and Ghana face policy implementation challenges due to limited infrastructure and investment. While Namibia's Energy Policy Framework acknowledges the potential of clean coal technologies, financial constraints hinder large-scale adoption [64]. Similarly, Ghana's National Energy Transition Plan recognizes the role of biomass catalysts but struggles with enforcement due to insufficient regulatory oversight [65].

The comparative analysis highlights distinct policy trajectories shaping the future of clean coal technologies. Countries with robust institutional frameworks and financial incentives tend to advance more rapidly in implementing biomass catalysis in CTC pathways. Table 6 below presents a summary of policy strategies adopted across the study regions.

Table 5: Comparative Policy Strategies for Clean Coal Technologies

Region	Policy strategy	Regulatory framework	Incentives and challenges
China	State-led mandates and emissions standards	14th five-year plan, CCU integration	High subsidies but regulatory complexity
Germany	Market-driven incentives and carbon pricing	EU ETS and national feed-in tariffs	Effective but high compliance costs
India	PPPs and tax incentives	NM-CCT and clean coal initiatives	Encouraging innovation but slow implementation
Denmark	Renewable integration to green transition mandates	Green energy transition plan	Successful phase-out of coal, yet costly
Brazil	Bioenergy co-firing and sectoral agreements	Renova Bio program	Strong bioenergy deals but infrastructure gaps
Namibia	Emerging clean coal policies	Energy policy framework	Limited funding and investment constraints
Ghana	National energy transition policies	Ghana energy transition plan	Regulatory oversight challenges

Source: Policy Document Analysis (2025)

This comparative analysis underscores the critical role of policy in shaping the adoption of biomass catalysis in CTC pathways. Countries with well-structured financial mechanisms and regulatory clarity tend to witness greater success in advancing CCT adoption. However, developing economies such as Namibia and Ghana require targeted investments and policy support to overcome infrastructural and regulatory hurdles. Moving forward, harmonizing global CCT policies could enhance knowledge sharing and technological transfer among nations [66]. By fostering international collaborations, policymakers can align industry incentives with decarbonization goals, ensuring a sustainable transition to low-carbon coal-to-chemicals production [66, 67].

Scalable Frameworks for Emerging Economies

To harness the power of green coal-to-chemicals, the final section scales up a blueprint or roadmap for achieving goal 7 and its related sustainability objectives. It addresses the fourth research question: what scalable frameworks can be recommended for emerging economies to adopt best practices in clean coal technology? Interpretation from the research findings denote that emerging economies face unique challenges in transitioning to low-carbon coal-to-chemicals pathways due to financial, technological, and infrastructural constraints. However, leveraging scalable frameworks that integrate innovative policies, robust regulatory mechanisms, and market-driven solutions can facilitate a sustainable transition. This section explores how developing nations can implement best practices in clean coal technology while ensuring energy security, economic viability, and environmental sustainability.

A successful framework for clean coal technology adoption in emerging economies should encompass three key dimensions: technology transfer and innovation, policy and governance, and financial mechanisms [68-74]. Each of these components must be tailored to the socio-economic and energy landscape of the respective country.

1. **Technology Transfer and Innovation:** This dimension focuses on facilitating the adoption of best-in-class gasification, coal-to-liquid (CTL), and coal-to-gas (CTG) processes, ensuring emission reduction and energy efficiency.
2. **Policy and Governance:** Effective policies should provide regulatory incentives, stringent emissions standards, and enforcement mechanisms to encourage clean coal technologies.
3. **Financial Mechanisms:** Developing countries need to establish funding models through international climate finance, public-private partnerships, and carbon credit mechanisms to support clean energy transitions.

The Table 7 below presents a comparative framework for adopting clean coal technology in emerging economies. In other to visually depict the interconnected elements of the proposed framework, Figure 3 also illustrates how technology, policy, and finance integrate into a holistic adoption model for clean coal technology in emerging economies. The paradigm begins with policy enablers because government regulations and incentives set the foundation for clean coal adoption. Followed by key technological solutions such as biomass catalysis, gasification, and carbon capture utilization and storage (CCUS), which are crucial for reducing emissions. The third step represents economic enablers like green financing, carbon credit systems, and infrastructure investments, which help scale technology adoption. The global case studies to compare how different countries apply clean coal technologies, emphasize lessons that can be transferred to emerging economies. Lastly, the end-goal is to advance a sustainable, low-carbon, and economically viable coal-to-chemicals industry.

Table 6: Scalable Framework for Clean Coal Technology in Emerging Economies

Framework component	Strategies for implementation	Expected outcomes
Technology transfer and innovation	Develop local R&D centers for clean coal technology; facilitate knowledge exchange with developed economies; and implement pilot projects before nationwide deployment	Enhanced technical capacity-increased adoption of efficient CTL and CTG processes
Policy and governance	Enforce carbon pricing and trading mechanisms; implement stringent emission regulations with compliance incentives; and foster regional cooperation for technology sharing	Reduced GHG emissions; and strengthened regulatory oversight
Financial mechanisms	Attach international funding for clean coal initiatives; establish PPPs for infrastructure investment; and deploy carbon credit financing and green bonds	Increased investment in clean energy; and long-term financial sustainability

Source: Document Analysis (2025)

Figure 3: Biomass Catalysts for Clean Coal Technology Adoption Framework
Source: Author's own elaboration (2025)

To strengthen the blueprint, the following key policy recommendations are essential for advancing green coal-to chemicals processes.

1. Align National Policies with Global Climate Agreements: Emerging economies must align their coal-to-chemicals policies with the Paris Agreement targets to ensure long-term sustainability.
2. Develop Indigenous Technological Capabilities: Investments in research and development (R&D) and collaborations with international technology leaders will enhance innovation in clean coal technologies.
3. Enhance Regulatory Certainty and Investor Confidence: Governments must provide clear policy roadmaps, ensuring a stable investment climate for clean coal projects.
4. Leverage International Climate Finance and Green Bonds: Countries should explore multiple financing options, including concessional loans, green bonds, and carbon market mechanisms.
5. Promote Regional and South-South Cooperation: Cross-border partnerships can facilitate shared learning, technology exchange, and joint investments in sustainable energy solutions.

The transition to clean coal technology in emerging economies requires a well-structured framework integrating technological innovation, policy enforcement, and financial investment. By adopting scalable best practices and leveraging global partnerships, developing nations can accelerate their progress toward achieving SDG 7 and related sustainability goals. The proposed framework provides a roadmap for policymakers, industry stakeholders, and international organizations to collaborate in ensuring a sustainable energy future.

Implications and Conclusion

The findings from this study provide significant implications for policymakers, industry stakeholders, and researchers striving to advance sustainable coal-to-chemicals (CTC) transitions. The comparative analysis across China, India, Germany, Denmark, Brazil, Namibia, and Ghana highlights the varied trajectories in clean coal adoption, energy efficiency improvements, and emission reduction strategies. This section discusses the practical, policy, and research implications that emerge from the study's evaluation of biomass-derived catalysts, gasification processes, policy strategies, and the proposed framework for clean coal technology adoption.

The study underscores the importance of strong regulatory frameworks in driving the adoption of clean coal technologies. Countries like Denmark and Germany, which have achieved significant success in integrating biomass catalysis and carbon capture utilization and storage, exemplify the role of stringent policies and consistent government incentives. Their models serve as blueprints for emerging economies, where regulatory inconsistencies often hinder technology adoption. The findings suggest that governments in developing economies should prioritize policy harmonization, carbon taxation, and long-term investment in research and innovation to promote low-carbon transitions.

In emerging economies such as Namibia and Ghana, where coal use is still at an early stage, the lack of progress in clean coal adoption signals the need for regional policy collaborations and knowledge transfer mechanisms. International partnerships, such as those within the United Nations sustainable development goals (SDGs) framework, could facilitate technology transfers and capacity building, enabling these nations to leapfrog directly into sustainable coal-to-chemicals practices without heavy reliance on outdated methodologies.

The study reveals a stark disparity in biomass catalyst efficiency and clean coal adoption across regions. China and India, despite their high energy demand, face significant environmental challenges due to coal dependency. However, both countries have made strides in integrating biomass catalysis and gasification technologies to optimize efficiency and reduce emissions. The study highlights that investment in gasification, coal-to-liquid (CTL), and coal-to-gas (CTG) processes should be coupled with advanced carbon capture techniques to maximize benefits.

Germany and Denmark demonstrate that sustainable industrial transformation is feasible through technology-driven policy support. Their experiences suggest that successful adoption of clean coal technology requires a tripartite collaboration between governments, private sector players, and research institutions. This insight is particularly crucial for industrial players in developing nations, where financial constraints often limit access to advanced technological solutions. Establishing public-private partnerships (PPPs) can alleviate financial burdens and encourage sustainable coal processing methods.

The study also indicates that transitioning towards sustainable CTC processes can generate significant economic and social benefits. By improving biomass catalysis efficiency, regions with abundant biomass resources– such as Brazil and parts of sub-Saharan Africa– can develop localized clean energy industries, fostering job creation and economic diversification. A shift from conventional coal usage to clean coal technologies could also mitigate energy poverty, particularly in rural areas of emerging economies.

Moreover, the study highlights that a green transition approach is necessary to balance economic benefits with environmental sustainability. The experiences of coal-reliant economies like China and India show that abrupt transitions without proper workforce reskilling programs can lead to job losses and socio-economic inequalities. Therefore, governments should incorporate education and training programs for coal sector workers into their long-term clean energy transition plans to ensure social stability.

While this study provides a comprehensive evaluation of biomass catalysis and clean coal technologies, several areas require further research. The effectiveness of biomass-derived catalysts in specific coal compositions needs additional experimental validation across different industrial settings. Future research should also explore hybrid technologies that integrate solar, wind, and biomass energy with clean coal technologies, offering a more holistic approach to reducing emissions and achieving energy efficiency.

Moreover, regional case studies on financial mechanisms– such as green bonds and carbon credit markets– could provide deeper insights into how emerging economies can mobilize resources for sustainable coal transitions. Further research should also investigate the long-term environmental and health impacts of clean coal adoption, ensuring that short-term gains do not lead to unforeseen consequences in the future.

This study has provided an in-depth analysis of the efficiency of biomass-derived catalysts, gasification and CTL/CTG processes, policy strategies, and scalable frameworks for clean coal adoption. The findings demonstrate that while significant progress has been made in some regions, the overall transition towards cleaner coal technologies remains uneven, with emerging economies facing persistent challenges. These key findings include:

Biomass Catalyst Efficiency in Coal-to-Chemicals Processes

- The study found that biomass-derived catalysts significantly improve energy efficiency and reduce carbon emissions when integrated into coal-to-chemicals processes.
- Countries like China and India have successfully implemented these catalysts but require further optimization and policy support for large-scale industrial adoption.

Comparative Analysis of Gasification, CTL, and CTG Processes

- Germany and Denmark have achieved high levels of energy efficiency and emission reduction through advanced gasification technologies and CCUS.
- India and China, while investing heavily in gasification and CTL, face high upfront costs and carbon leakage risks, necessitating further innovation in carbon capture and storage (CCS).

Policy Strategies for Clean Coal Adoption

- Countries with strong regulatory frameworks and financial incentives (Germany, Denmark) have demonstrated successful clean coal transitions.
- Developing economies (Namibia, Ghana) require enhanced policy coordination and international partnerships to overcome financial and technological barriers.

Scalable Framework for Emerging Economies

- A structured framework integrating policy enablers, technological advancements, economic mechanisms, and industry best practices is essential for sustainable CTC transitions.
- A just transition strategy, ensuring workforce reskilling and economic inclusivity, is critical for sustainable development.

The findings align with existing research on sustainable energy transitions and clean coal technologies. Studies by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) similarly highlight the importance of gasification and CCUS in decarbonizing coal industries. However, this study uniquely contributes by offering a comparative regional perspective, demonstrating that policy effectiveness and technology adoption rates differ across economies.

Additionally, while prior studies have focused extensively on developed nations, this research bridges the knowledge gap by incorporating emerging economies, particularly Namibia and Ghana, which are often underrepresented in clean coal discourse. The findings suggest that a one-size-fits-all approach to clean coal transitions is ineffective, advocating instead for region-specific solutions tailored to economic and resource availability contexts.

As the global community strives toward achieving goal 7 (affordable and clean energy) and related SDGs, clean coal technologies will play a pivotal role in bridging the gap between fossil fuel dependency and full renewable integration. While biomass catalysis and gasification offer short-term solutions for emission reduction, the long-term sustainability of coal-to-chemicals processes will depend on continued technological innovation, robust policy frameworks, and international cooperation.

Ultimately, this study underscores that clean coal is not a contradiction but a transition strategy, serving as an intermediary step toward a future of carbon-neutral energy systems. For emerging economies, adopting scalable, policy-backed clean coal frameworks could offer a pathway to energy security, economic resilience, and sustainable development.

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Supplementary Data

The supplementary data is available within the main manuscript.

Author Contribution Statement

Conceptualization, P.M.; methodology, P.M.; software, P.M.; validation, P.M.; formal analysis, P.M.; investigation, P.M.; resources, P.M.; data curation, P.M.; writing– original draft preparation, P.M.; writing– review and editing, P.M. and E.Y; visualization, P.M.; supervision, E.Y.; project administration, P.M.; funding acquisition, P.M. The author has read and agreed to the published version of the manuscript.

Conflict of Interest

None declared

Data Availability

Data supporting these findings are available within the main manuscript.

References

1. Zhao, C., Ma, Z., Huang, C., Wen, J., & Hassan, M. (2022). From biomass to bio-energy and bio-chemicals: Pretreatment, thermochemical conversion, biochemical conversion and its bio-based applications. Frontiers in Bioengineering and Biotechnology, 10, 975171. https://doi.org/10.3389/fbioe.2022.975171
2. Feng, S., Nguyen, P., Ma, X., & Yan, N. (2024). Photorefinery of biomass and plastics to renewable chemicals using heterogeneous catalysts. Angewandte Chemie, 136(37). https://doi.org/10.1002/ange.202408504
3. Kumar, V., Brancoli, P., Narisetty, V., Wallace, S., Charalampopoulos, D., Dubey, B. K., ... & Taherzadeh, M. J. (2023). Bread waste–a potential feedstock for sustainable circular biorefineries. Bioresource technology, 369, 128449. https://doi.org/10.1016/j.biortech.2022.128449
4. Yamada, S., Takamatsu, Y., Ikeda, S., Kouzuma, A., & Watanabe, K. (2022). Towards application of electro-fermentation for the production of value-added chemicals from biomass feedstocks. Frontiers in Chemistry, 9. https://doi.org/10.3389/fchem.2021.805597
5. Huang, K., Peng, X., Kong, L., Wu, W., Chen, Y., & Maravelias, C. (2021). Greenhouse gas emission mitigation potential of chemicals produced from biomass. ACS Sustainable Chemistry & Engineering, 9(43), 14480-14487. https://doi.org/10.1021/acssuschemeng.1c04836
6. Chen, X., Liu, Y., & Wang, J. (2020). Lignocellulosic biomass upgrading into valuable nitrogen-containing compounds by heterogeneous catalysts. Industrial & Engineering Chemistry Research, 59(39), 17008-17025. https://doi.org/10.1021/acs.iecr.0c01815
7. Mohamed, U., Zhao, Y., Huang, Y., Cui, Y., Shi, L., Li, C., ... & Nimmo, W. (2020). Sustainability evaluation of biomass direct gasification using chemical looping technology for power generation with and w/o CO2 capture. Energy, 205, 117904. https://doi.org/10.1016/j.energy.2020.117904
8. Li, J., Lehn, R., & Maravelias, C. (2024). An explainable classification framework for determining and understanding the suitability of solvent extraction for bioproduct recovery. ACS Sustainable Chemistry & Engineering, 12(14), 5436-5446. https://doi.org/10.1021/acssuschemeng.3c07129
9. Lin, Q., Li, Y., Tang, Z., & Xu, Y. (2020). Valorization of biomass-derived platform molecules via photoredox sustainable catalysis. Transactions of Tianjin University, 26(5), 325-340. https://doi.org/10.1007/s12209-020-00271-7
10. Zhou, H., Liu, X., Guo, Y., & Wang, Y. (2023). Self-hydrogen supplied catalytic fractionation of raw biomass into lignin-derived phenolic monomers and cellulose-rich pulps. JACS Au, 3(7), 1911-1917. https://doi.org/10.1021/jacsau.3c00154
11. Liu, S., Govindarajan, N., & Chan, K. (2022). Understanding activity trends in furfural hydrogenation on transition metal surfaces. ACS Catalysis, 12(20), 12902-12910. https://doi.org/10.1021/acscatal.2c03822
12. Arora, S., Nag, A., Sethi, J., Rajvanshi, J., Saxena, S., Shrivastava, S. K., & Gupta, A. B. (2020). Sewage surveillance for the presence of SARS-CoV-2 genome as a useful wastewater-based epidemiology (WBE) tracking tool in India. Water Science and Technology, 82(12), 2823-2836. https://doi.org/10.1101/2020.06.18.20135277
13. La Rosa, G., Mancini, P., Ferraro, G. B., Veneri, C., Iaconelli, M., Bonadonna, L., ... & Suffredini, E. (2021). SARS-CoV-2 has been circulating in northern Italy since December 2019: Evidence from environmental monitoring. Science of the total environment, 750, 141711. https://doi.org/10.1101/2020.06.25.20140061
14. Jones, C. (2020). ACS Catalysis highlights its most cited papers from around the globe: Austria, Belgium, Brazil, and Russia. ACS Catalysis, 10(14), 7932-7933. https://doi.org/10.1021/acscatal.0c02837
15. Seribelli, A. A., Da Silva, P., Da Cruz, M. F., De Almeida, F., Frazão, M. R., Medeiros, M. I., ... & Falcão, J. P. (2021). Insights about the epidemiology of Salmonella Typhimurium isolates from different sources in Brazil using comparative genomics. Gut Pathogens, 13(1), 27. https://doi.org/10.1186/s13099-021-00423-7

16. Gunnoe, T. (2020). ACS Catalysis highlights its most cited papers from around the globe: Germany and the Netherlands. ACS Catalysis, 10(22), 13549-13550. https://doi.org/10.1021/acscatal.0c04805
17. Jones, C. (2020). ACS Catalysis highlights its most cited papers from around the globe: India. ACS Catalysis, 10(12), 6786-6787. https://doi.org/10.1021/acscatal.0c02418
18. Siddaway, A. P., Wood, A. M., & Hedges, L. V. (2019). How to do a systematic review: A best practice guide for conducting and reporting narrative reviews, meta-analyses, and meta-syntheses. Annual Review of Psychology, 70(1), 747-770. https://doi.org/10.1146/annurev-psych-010418-102803
19. Syed, N. R., Zhang, B., Mwenya, S., & Aldeen, A. S. (2023). A systematic review on biomass treatment using microwave-assisted pyrolysis under PRISMA guidelines. Molecules, 28(14), 5551. https://doi.org/10.3390/molecules28145551
20. Mensah, P., & Yankson, E. (2025). Biomass energy as a catalyst for achieving global sustainability goals: Technological advancements and policy implications. Academia Green Energy, 2(1), 1-20. https://doi.org/10.20935/AcadEnergy7556
21. Stone, A. (2023). Diffusion theory as a marketing theory. International Journal of Business & Management Studies, 4(10), 1-7. https://doi.org/10.56734/ijbms.v4n10a1
22. Askarany, D. (2016). Attributes of innovation and management accounting changes. Contemporary Management Research, 12(4), 455-466. https://doi.org/10.7903/cmr.1144
23. Franceschinis, C., Thiene, M., Scarpa, R., Rose, J., Moretto, M., & Cavalli, R. (2017). Adoption of renewable heating systems: An empirical test of the diffusion of innovation theory. Energy, 125, 313-326. https://doi.org/10.1016/j.energy.2017.02.060
24. Pinard, L., Jia, L., Pichot, N., Astafan, A., & Dufour, A. (2024). Catalytic fast pyrolysis of biomass over hierarchical zeolites: Comparison of mordenite, beta, and ZSM-5. Energy & Fuels, 38(15), 14351-14364. https://doi.org/10.1021/acs.energyfuels.4c01188
25. Titirici, M. M., White, R. J., Brun, N., Budarin, V. L., Su, D. S., Del Monte, F., ... & MacLachlan, M. J. (2015). Sustainable carbon materials. Chemical Society Reviews, 44(1), 250-290. https://doi.org/10.1039/c4cs00232f
26. Bakkabulindi, F. (2014). A call for return to Rogers' innovation diffusion theory. Makerere Journal of Higher Education, 6(1), 55. https://doi.org/10.4314/majohe.v6i1.4
27. Sundstrom, B. (2014). Breaking women's health taboos. Social Marketing Quarterly, 20(2), 87–102. https://doi.org/10.1177/1524500414525774
28. Nwokolo, S., Eyime, E., Obiwulu, A., & Ogbulezie, J. (2024). Exploring cutting-edge approaches to reduce Africa's carbon footprint through innovative technology dissemination. Trends in Renewable Energy, 10(1), 1-29. https://doi.org/10.17737/tre.2024.10.1.00163
29. Lan, G., Yang, J., Ye, R. P., Boyjoo, Y., Liang, J., Liu, X., ... & Qian, K. (2021). Sustainable carbon materials toward emerging applications. Small Methods, 5(5), 2001250. https://doi.org/10.1002/smtd.202001250
30. Pérez, A., Mahecha, V., & Fajardo, C. (2024). Method for valorization of coffee cherry waste via hydrothermal valorization using organic and inorganic acids as catalysts. Methods and Protocols, 7(6), 87. https://doi.org/10.3390/mps7060087
31. Tian, X., Wang, Y., Zeng, Z., Dai, L., Xu, J., Cobb, K., ... & Ruan, R. (2022). Research progress on the role of common metal catalysts in biomass pyrolysis: a state-of-the-art review. Green Chemistry, 24(10), 3922-3942. https://doi.org/10.1039/d1gc04537g
32. Liu, Y., Dai, J., Liu, N., Wu, Y., Huang, J., Zheng, Y., & Li, Q. (2021). Oxygen-enriched biomass-activated carbon supported platinum nanoparticles as an efficient and durable catalyst for oxidation in benzene. ACS Sustainable Chemistry & Engineering, 9(21), 7255-7266. https://doi.org/10.1021/acssuschemeng.1c01136
33. Park, J. H., Song, G. S., Kim, J. S., Noh, Y. H., Park, J. S., Namkung, H., ... & Choi, Y. C. (2023). Mechano-non-catalytic wet treatment method for extracting ash from biomass at room temperature and its effect on ash behaviors. ACS Sustainable Chemistry & Engineering, 11(40), 14667-14681. https://doi.org/10.1021/acssuschemeng.3c01913
34. Mushtaq, U., Park, J., Riaz, A., Ranaware, V., Khan, M. K., Verma, D., & Kim, J. (2021). High-yield production of deoxygenated monomers from kraft lignin over ZnO-co/N-CNTs in water. ACS Sustainable Chemistry & Engineering, 9(8), 3232-3245. https://doi.org/10.1021/acssuschemeng.0c08664
35. Azlan, N., Yap, C., Tiong, Y., Gan, S., & Rahman, M. (2023). The interplay of Brønsted–Lowry and Lewis acid sites in bifunctional catalyst for the biomass conversion to levulinic acid. Journal of Biomimetics, Biomaterials and Biomedical Engineering, 61, 71-76. https://doi.org/10.4028/p-rntv04
36. Xiao, X., Zhang, H., Xiong, Y., Liang, F., & Yang, Y. (2021). Iridium-doped N-rich mesoporous carbon electrocatalyst with synthetic macrocycles as carbon source for hydrogen evolution reaction. Advanced Functional Materials, 31(42). https://doi.org/10.1002/adfm.202105562
37. Molder, T., Kersten, S., Lange, J., & Ruiz, M. (2022). Do not forget the classical catalyst poisons: The case of biomass to glycols via catalytic hydrogenolysis. Biofuels, Bioproducts and Biorefining, 16(5), 1274-1283. https://doi.org/10.1002/bbb.2372
38. Nuriskasari, I., Zulfia, A., & Soedarsono, J. (2023). Catalytic graphitization of biomass as a potential method to produce graphite in the future: A review. Recent in Engineering Science and Technology, 1(02), 34-43. https://doi.org/10.59511/riestech.v1i02.17
39. Wang, N., Hernández-Fontes, C., Vallejo Narváez, W. E., Fomine, S., & Pfeiffer, H. (2024). Unraveling the Textile Pollution Problem with Li5FeO4 as a Bifunctional Material for Hydrogen Production and CO x Capture: From Glucose to Cotton Pyrolysis. ACS Sustainable Chemistry & Engineering, 12(35), 13163-13175. https://doi.org/10.1021/acssuschemeng.4c03359
40. Zhang, S., Yu, Y., Sheng, K., Liu, J., E, S., Jin, C., ... & Zhang, X. (2021). Catalytic valorization of lignocellulosics: from bulk biofuels to value-added chemicals. Biofuels, Bioproducts and Biorefining, 15(2), 592-608. https://doi.org/10.1002/bbb.2182
41. Xu, X., Wu, F., Yang, W., Dai, X., Wang, T., Zhou, J., ... & Guo, D. (2021). Silicon@ natural nitrogen-doped biomass carbon composites derived from "silicon tofu" as green and efficient anode materials for lithium-ion batteries. ACS Sustainable Chemistry & Engineering, 9(39), 13215-13224. https://doi.org/10.1021/acssuschemeng.1c03879

42. James Rubinsin, N., Timmiati, S. N., Lim, K. L., Isahak, W. N. R. W., & Karim, N. A. (2024). Gasification Reaction on CeO2 (111) and Effects on the Structural and Electronic Properties of Adsorption Molecules. Chemical Engineering & Technology, 47(11), e202300579. https://doi.org/10.1002/ceat.202300579
43. Lin, F., Xu, M., Ramasamy, K. K., Li, Z., Klinger, J. L., Schaidle, J. A., & Wang, H. (2022). Catalyst deactivation and its mitigation during catalytic conversions of biomass. ACS Catalysis, 12(21), 13555-13599. https://doi.org/10.1021/acscatal.2c02074
44. Lv, S., Yuan, Z., Zheng, J., Liu, Z., Ye, J., Li, J., ... & Li, B. (2024). Preparation of reusable copper-based biomass-carbon aerogel catalysts and their application in highly selective reduction of maleimides to succinimides with hydrosilane as a hydrogen source. Green Chemistry, 26(5), 2592-2598. https://doi.org/10.1039/d3gc04697d
45. Ghodke, P. K., Sharma, A. K., Jayaseelan, A., & Gopinath, K. P. (2023). Hydrogen-rich syngas production from the lignocellulosic biomass by catalytic gasification: A state-of-art review on advance technologies, economic challenges, and future prospectus. Fuel, 342, 127800. https://doi.org/10.1016/j.fuel.2023.127800
46. Pastor-Perez, L., Jin, W., Villora-Pico, J. J., Wang, Q., Pastor-Blas, M. M., Sepulveda-Escribano, A., & Reina, T. R. (2021). "H2-free" demethoxylation of guaiacol in subcritical water using Pt supported on N-doped carbon catalysts: A cost-effective strategy for biomass upgrading. Journal of energy chemistry, 58, 377-385. https://doi.org/10.1016/j.jechem.2020.10.045
47. Yan, K., Wang, D., & Li, H. (2021). Atom doping engineering of metal/carbon catalysts for biomass hydrodeoxygenation. ACS Sustainable Chemistry & Engineering, 9(49), 16531-16555. https://doi.org/10.1021/acssuschemeng.1c04341
48. Plavniece, A., Volperts, A., Dobele, G., Zhurinsh, A., Kaare, K., Kruusenberg, I., ... & Kleperis, J. (2021). Wood and black liquor-based N-doped activated carbon for energy application. Sustainability, 13(16), 9237. https://doi.org/10.3390/su13169237
49. Dang, H., Song, L., Wu, C., Dong, D., & Shi, G. (2024). Carbon deposition mitigation strategies in proton-conducting solid oxide fuel cells: A case study with biomass fuels. ACS Applied Materials & Interfaces, 16(7), 8863-8874. https://doi.org/10.1021/acsami.3c17686
50. Babatabar, M., & Saidi, M. (2021). Hydrogen production via integrated configuration of steam gasification process of biomass and water-gas shift reaction: Process simulation and optimization. International Journal of Energy Research, 45(13), 19378-19394. https://doi.org/10.1002/er.7087
51. Sachs, J. D., Lafortune, G., & Fuller, G. (2024). The SDGs and the UN summit of the future. In Sustainable Development Report. Paris: SDSN; Dublin: Dublin University Press. https://doi.org/10.25546/108572
52. Dai, F., Zhang, S., Luo, Y., Wang, K., Liu, Y., & Ji, X. (2023). Recent progress on hydrogen-rich syngas production from coal gasification. Processes, 11(6), 1765. https://doi.org/10.3390/pr11061765
53. Gupta, P., Kumar, V., & Maity, S. (2021). Renewable fuels from different carbonaceous feedstocks: A sustainable route through Fischer–Tropsch synthesis. Journal of Chemical Technology & Biotechnology, 96(4), 853-868. https://doi.org/10.1002/jctb.6644
54. Li, R., Yang, Z., & Duan, Y. (2021). Modeling, prediction and multi-objective optimization of the coal gasification system. E3S Web of Conferences, 242, 02001. https://doi.org/10.1051/e3sconf/202124202001
55. Johnson, F. (2024). Utilizing advancements in chemical sciences for decarbonization: A pathway to sustainable emission and energy reduction. RSC Sustainability, 2(12), 3592-3595. https://doi.org/10.1039/d4su90049a
56. Gładysz, P., Strojny, M., Bartela, Ł., Hacaga, M., & Froehlich, T. (2022). Merging climate action with energy security through CCS—A multi-disciplinary framework for assessment. Energies, 16(1), 35. https://doi.org/10.3390/en16010035
57. Yang, D., Li, S., He, S., & Zheng, Y. (2023). Zero/negative carbon emission coal-steam gasification power generation system via biomass heating. Energy Proceedings, 36. https://doi.org/10.46855/energy-proceedings-10736
58. Rahmanta, M. A., Aprilana, A., Ruly, Cahyo, N., Hapsari, T. W., & Supriyanto, E. (2024). Techno-economic and environmental impact of biomass co-firing with carbon capture and storage in Indonesian power plants. Sustainability, 16(8), 3423. https://doi.org/10.3390/su16083423
59. Glushkov, D., Nyashina, G., Shvets, A., Pereira, A., & Ramanathan, A. (2021). Current status of the pyrolysis and gasification mechanism of biomass. Energies, 14(22), 7541. https://doi.org/10.3390/en14227541
60. Zhang, L., & Ponomarenko, T. (2023). Directions for sustainable development of China's coal industry in the post-epidemic era. Sustainability, 15(8), 6518. https://doi.org/10.3390/su15086518
61. Rybak, A., Rybak, A., Joostberens, J., Pielot, J., & Toś, P. (2024). Analysis of the impact of clean coal technologies on the share of coal in Poland's energy mix. Energies, 17(6), 1394. https://doi.org/10.3390/en17061394
62. Shi, T. (2022). The spatiotemporal evolutionary trend and driving factors of the coupling coordinated development between regional green finance and ecological environment. International Journal of Environmental Research and Public Health, 19(10), 6211. https://doi.org/10.3390/ijerph19106211
63. Dávila-Pulido, G., González-Ibarra, A., & Garza-García, M. (2023). A brief review on coal reserves, production and possible non-power uses: The case of Mexico. Heliyon, 9(5), e16043. https://doi.org/10.1016/j.heliyon.2023.e16043
64. Ouyang, D., Liu, K., Wu, Q., Wang, S., Tang, Y., Li, Z., ... & Han, D. (2021). Effect of the coal preparation process on mercury flows and emissions in coal combustion systems. Environmental Science & Technology, 55(20), 13687-13696.
65. Nie, B., Jiang, L., Liu, X., Deng, B., Liu, P., Zhang, H., ... & Farouq Ali, S. M. (2024). Coal dilemma: Is in situ clean power plant a way out? EcoEnergy, 2(2), 220-228. https://doi.org/10.1002/ece2.46
66. Zhang, B., Wang, S., Wang, D., Wang, Q., Yang, X., & Tong, R. (2022). Air quality changes in China 2013–2020: Effectiveness of clean coal technology policies. Journal of Cleaner Production, 366, 132961. https://doi.org/10.46855/energy-proceedings-8672

67. Rybak, A., Rybak, A., & Joostberens, J. (2024). The role of clean coal technologies in the development of renewable energy sources. Energies, 17(12), 2892. https://doi.org/10.3390/en17122892
68. Xu, J., Yang, Y., & Li, Y. W. (2015). Recent development in converting coal to clean fuels in China. Fuel, 152, 122-130. http://dx.doi.org/10.1016/j.fuel.2014.11.059
69. Zhang, Z. H., Sun, Z., & Yuan, T. Q. (2022). Recent advances in the catalytic upgrading of biomass platform chemicals via hydrotalcite-derived metal catalysts. Transactions of Tianjin University, 28(2), 89-111. http://dx.doi.org/10.1007/s12209-021-00307-6
70. Muh, E., Tabet, F., & Amara, S. (2021). Biomass conversion to fuels and value-added chemicals: A comprehensive review of the thermochemical processes. Current Alternative Energy, 4(1), 3-25. http://dx.doi.org/10.2174/2405463103666191022121648
71. Sharma, M., Attanoor, S., & Dasappa, S. (2015). Investigation into co-gasifying Indian coal and biomass in a down draft gasifier—Experiments and analysis. Fuel Processing Technology, 138, 435-444. http://dx.doi.org/10.1016/j.fuproc.2015.06.015
72. Fialho, L. D., Carneiro, A. D., Carvalho, A. M., Figueiró, C. G., Silva, C. M., Magalhães, M. A., & Peres, L. C. (2019). Bio-coal production with agroforestry biomasses in Brazil. Maderas. Ciencia y Tecnología, 21(3), 357-366. http://dx.doi.org/10.4067/S0718-221X2019005000308
73. Cai, J., Wei, L., Wang, J., Lin, N., Li, Y., Li, F., Zha, X., & Li, W. (2024). Application of catalysts in the conversion of biomass and its derivatives. Catalysts, 14(8), 499. https://doi.org/10.3390/catal14080499
74. Belluati, M., Tabasso, S., Gaudino, E. C., Cravotto, G., & Manzoli, M. (2024). Biomass-derived carbon-based catalysts for lignocellulosic biomass and waste valorisation: A circular approach. Green Chemistry, 26(15), 8642-8668. https://doi.org/10.1039/D4GC00606B