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Comprehensive analysis of tar reduction method in biomass gasification for clean energy production: A Review

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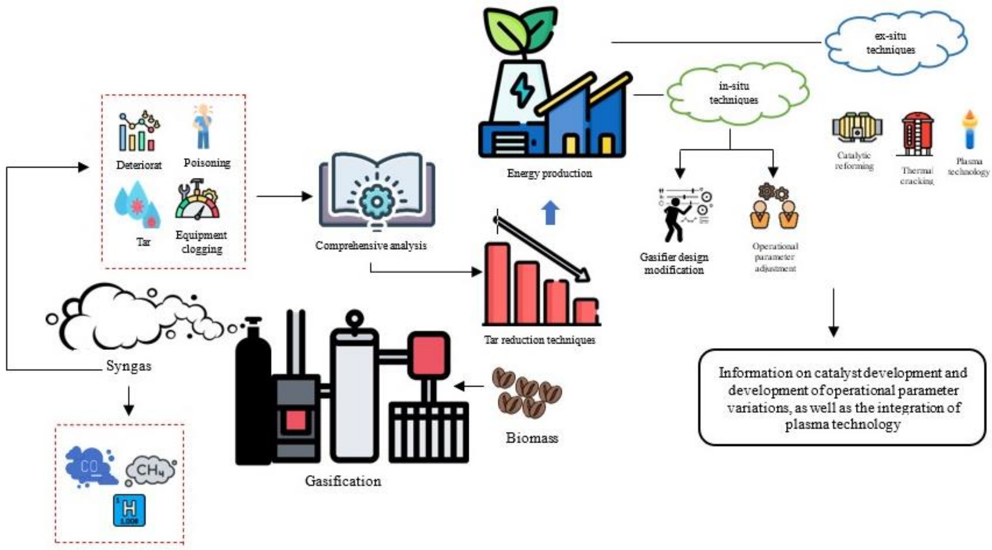

Highlights:
- Biomass gasification renewable energy technology for syngas production is quite promising but needs to be improved by reducing tar formation, which affects syngas quality.
- A comprehensive analysis of tar reduction technology was carried out by exploring in-situ (gasifier design, operational parameters) and ex-situ (catalytic reforming, thermal cracking, plasma technology) methods.
- An integrated optimization approach combining in-situ and ex-situ methods significantly improved syngas quality and system efficiency.

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Abstract
Biomass gasification is a promising renewable energy technology for the production of synthetic gas (syngas), consisting of hydrogen (H_2), carbon monoxide (CO), and methane (CH_4). This technology's primary challenge is tar formation – a heavy hydrocarbon compound that can block equipment, poison catalysts, and deteriorate syngas quality. Therefore, this study aimed to examine different tar reduction methods to support clean energy production through biomass gasification. To achieve this aim, two main approaches were adopted and the first was in-situ, focusing on modifying gasifier design and adjusting operational parameters. The second was ex-situ, which included catalytic reforming, thermal cracking, and plasma technology. The analysis also assessed different catalysts, such as biochar, and dolomite, as well as nickel- and iron-based materials, comparing their efficiency, sustainability, and economic viability. Several key factors influenced tar formation and reduction, namely feedstock type, operating temperature, air ratio, and reactor configuration. The result showed that combining in-situ and ex-situ technologies had substantial potential to significantly reduce tar, improve syngas quality, and optimize system performance. However, some challenges observed were reduced catalyst efficiency, high energy

costs, and the need for more sustainable technologies. To improve the performance of gasification systems, this study provided information on catalyst development, operational parameter optimization, and plasma technology integration. Finally, the analysis provided a scientific basis and strategic recommendations to overcome tar problems and encourage the commercial use of biomass gasification towards a clean energy transition.

Keywords: Biomass gasification; Tar reduction; Clean energy

1. Introduction

Biomass gasification is increasingly acknowledged as an effective renewable energy approach to reduce fossil fuel dependency and transition to clean energy sources [1]–[5]. This process converts biomass into synthetic gas (syngas), which is a mixture composed of hydrogen (H_2) [6], carbon monoxide (CO) [7], and methane (CH_4) [8], [9]. Syngas have diverse applications, serving as fuel for power generation, vehicle propulsion, and various industrial uses [10]–[15]. Despite its potential, biomass gasification faces a significant technical challenge in the formation of tar, a heavy hydrocarbon compound produced during pyrolysis [16]–[19]. These challenges include equipment blockage, catalyst poisoning, and deterioration of syngas quality, thereby impacting the efficiency and reliability of gasification system [12], [17], [20]–[23]. To address this issue, several tar cracking methods were developed in order to reduce excessive tar during gasification process [24]–[26].

Several previous studies have described the factors that influence tar formation and reduction. According to Jayanarasimhan et al. [27], tar concentration is influenced by the type of raw material, gasifier design, operating temperature, and gasification agent ratio. Furthermore, the study found that downdraft gasifiers generate significantly lower tar content (0.01–0.5 g/m^3) compared to fluidized bed gasifiers (5–40 g/m^3). This result emphasizes the critical role of selecting the right type of gasifier for specific applications. Zhao et al. [28] explored the optimization of three-stage biomass gasification in a 60 kW system using pine wood as the feedstock. The result showed that the use of an excess air coefficient (ER) of 0.35 produced gasification efficiency of 76.77% with a significant tar reduction rate of 99 mg/Nm^3. Computational Fluid Dynamics (CFD) simulations showed that tangential air injection at an angle of 30° improved the temperature distribution and facilitated tar cracking. Another study by Han and Kim [29] discussed tar reduction methods, namely catalytic reforming, thermal cracking, and plasma technology. In this context, nickel-based catalysts showed high efficiency (>90%) in tar reforming despite the challenge of catalyst deactivation due to carbon fouling. To ensure efficiency in tar management on a commercial scale, this study is a combination of in-situ and ex-situ methods. Another major concern in several studies is the use of biochar as a catalyst. Shen and Fu [17] identified biochar as an economical and environmentally friendly catalyst with the ability to reduce tar by more than 90% at 800°C. For instance, activation with steam and CO_2 increased the surface area and porosity of biochar, which had a positive impact on tar reforming efficiency. These findings strengthen the potential of biochar as an alternative to expensive and less environmentally friendly metal-based catalysts.

From the literature reviewed, biomass gasification has shown significant potential as a renewable energy technology for syngas production, as highlighted by various studies. However, the persistent tar formation problem continues to pose a challenge, which compromises the syngas quality and causes equipment failure. Based on insights from previous studies, such as the influence of feedstock type, gasifier design, and operational parameters on tar reduction, this study attempts to evaluate and integrate existing tar mitigation methods. These methods include in-situ techniques (gasifier design modification and operational adjustments) and ex-situ techniques (catalytic reforming, thermal cracking, and plasma technology). The motivation for this study arises from the need to identify gaps in current solutions while exploring sustainable and economically viable advances, including the use of alternative catalysts such as biochar, dolomite, nickel, and iron-based materials. By adopting an integrative approach, this study aims to identify potential improvements in syngas quality and efficiency of biomass gasification systems.

2. Methodology

In this work, we review tar reduction methods in biomass gasification through a systematic analysis of previous research. Two main strategies were identified: in-situ techniques focusing on gasifier design modifications, and ex-situ techniques including catalytic reactions, thermal cracking, and plasma treatment. The review evaluated the effectiveness, sustainability, and economic feasibility of these methods, along with the potential for combining in-situ and ex-situ strategies to enhance syngas quality and gasification efficiency. Figure 1 illustrates the methodological framework adopted in this study.

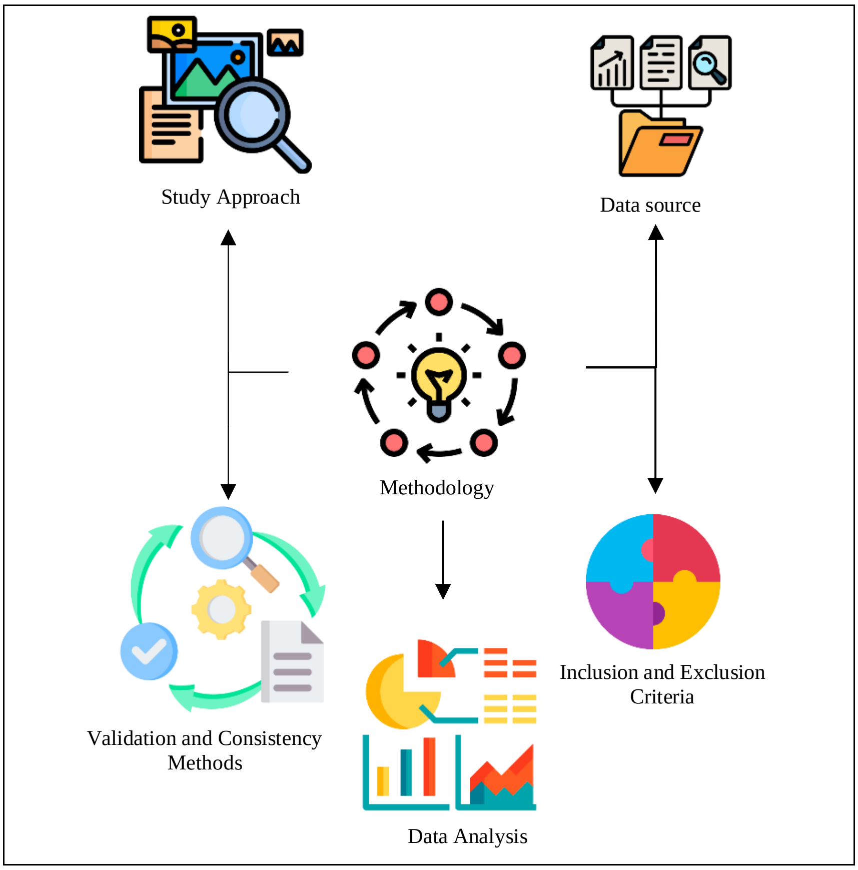

Figure 1. methodological framework adopted in this study

2.1. Data Sources

The litarature were obtained from scientific articles published in indexed international journals focusing on biomass gasification, tar reduction, and related technologies such as catalytic reforming and plasma technology. Literature searches were conducted in several leading scientific databases such as Google Scholar, ScienceDirect, and other reputable journals. This process aims to obtain up-to-date and relevant information on biomass gasification, syngas quality, in-situ and ex-situ tar reduction methods, along with the catalytic effects of tar reduction, as shown in Figure 1.

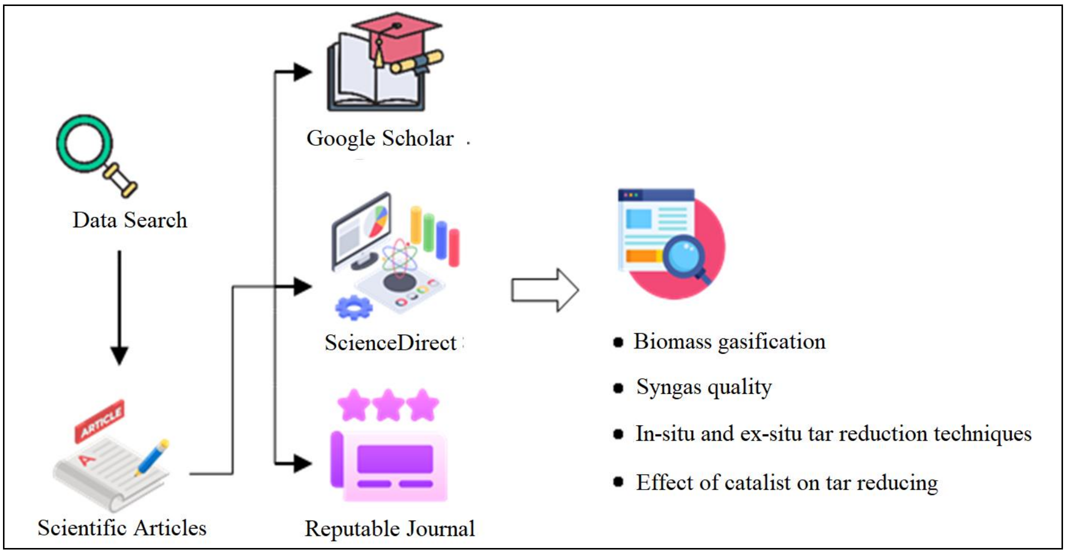

Figure 2. Literature search approach

2.2. Source Identification

The literature identification aimed to examine articles that discussed different tar reduction methods in biomass gasification and their impact on syngas quality. The search was conducted on articles published within a relevant timeframe to obtain relevant latest information in gasification. Furthermore, the search process was carried out to ensure that the articles found were relevant to tar reduction in biomass gasification. To ensure the quality and relevance of the literature, this study applied inclusion and exclusion criteria. Inclusion criteria comprised articles that discussed the latest technology, focusing on tar reduction in biomass gasification, and providing experimental data, simulations, or system analysis. Moreover, articles lacking quantitative data or that discussed only non-biomass gasification without tar reduction effects were excluded. After collecting scientific articles, a selection was conducted based on inclusion and exclusion criteria to ensure that the data used was of high quality and relevance. Figure 3 shows the workflow of the source identification process.

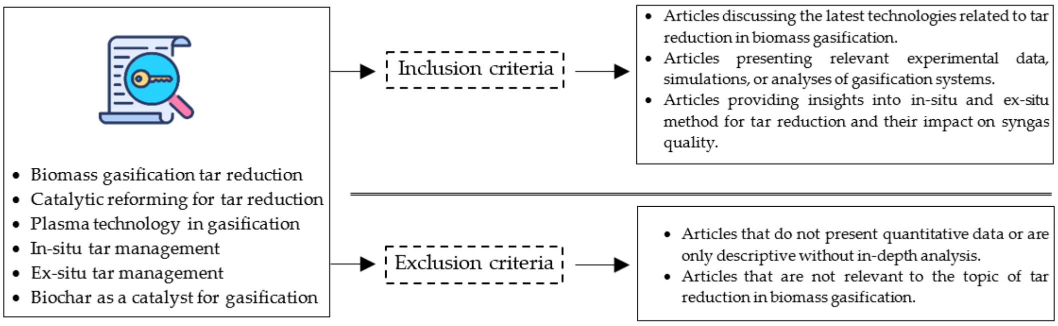

Figure 3. Workflow of the source identification process

2.3. Data Analysis

The first step consisted of collecting relevant scientific articles related to tar reduction in biomass gasification, followed by a screening process. This screening process began with reviewing the collected articles to ensure relevance through a systematic search in various scientific databases. The specific parameters analyzed were the success in reducing tar formation, the impact on the quality of syngas produced, as well as the challenges and potential for industrial-scale implementation of each tar reduction method. Subsequently, each article was analyzed to determine whether it met the inclusion and exclusion criteria. Articles that did not meet these criteria were excluded from further analysis. After the selection process, the articles that passed were considered for further analysis. The process of identifying important parameters for analysis is presented in Figure 4.

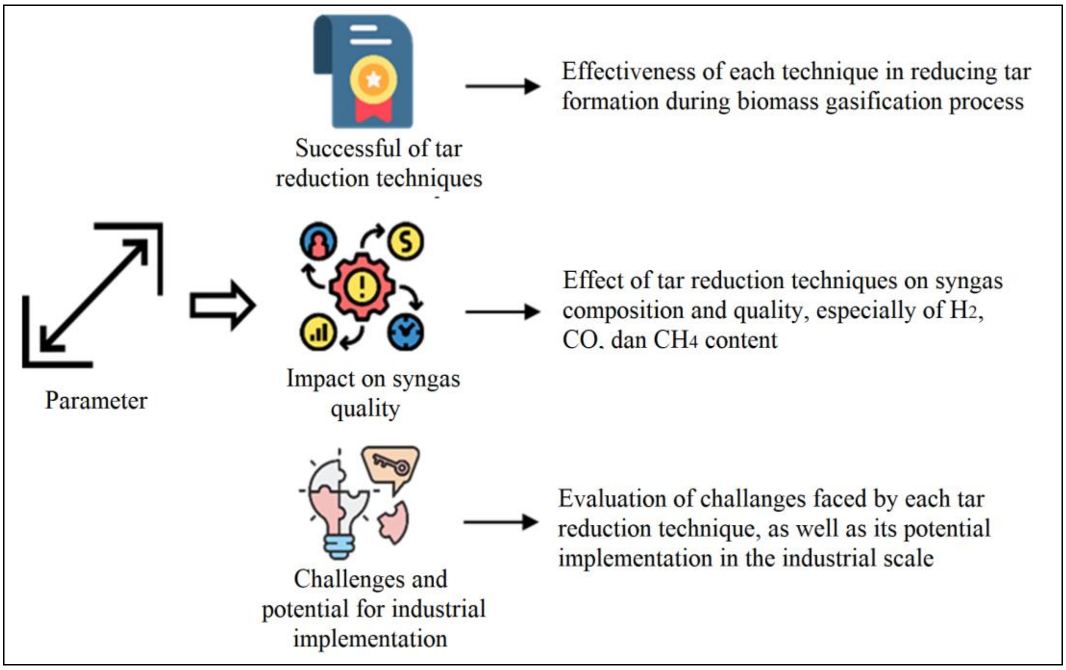

Figure 4. Process of identifying important parameters

2.4. Validation and Consistency

To ensure accuracy and reliability, data from various sources were cross-referenced. The synthesized findings were re-evaluated based on their relevance and contribution to the study objectives. This validation process ensured that the conclusions drawn were both precise and actionable. Any discrepancies identified during cross-referencing were addressed through iterative re-analysis.

3. Discussion

This discussion chapter focused on a detailed analysis of the articles selected for this study, as well as their relevance to the literature-based method. In this context, relevant articles related to the tar reduction method in biomass gasification were selected using strict inclusion criteria. The criteria included articles containing experimental data or analyses applied directly to tar reduction in biomass gasification. In particular, the discussion aimed to associate the main findings of the articles with the methodology adopted, to achieve more in-depth results. As explained in the method section, the current study used a literature-based approach to evaluate tar reduction methods, which were grouped into two main categories, namely in-situ and ex-situ.

This section provided a comprehensive examination of tar reduction methods in biomass gasification, obtained from the literature review. The discussion analyzed the in-situ and ex-situ tar reduction method, the efficacy of the catalyst, and the influence of operational parameters on the efficiency of the gasification system. Typically, these findings aimed to fulfill the objectives outlined in the introduction and to adjust with the previously established methodological stages. The discussion flow in this article is presented in Figure 5.

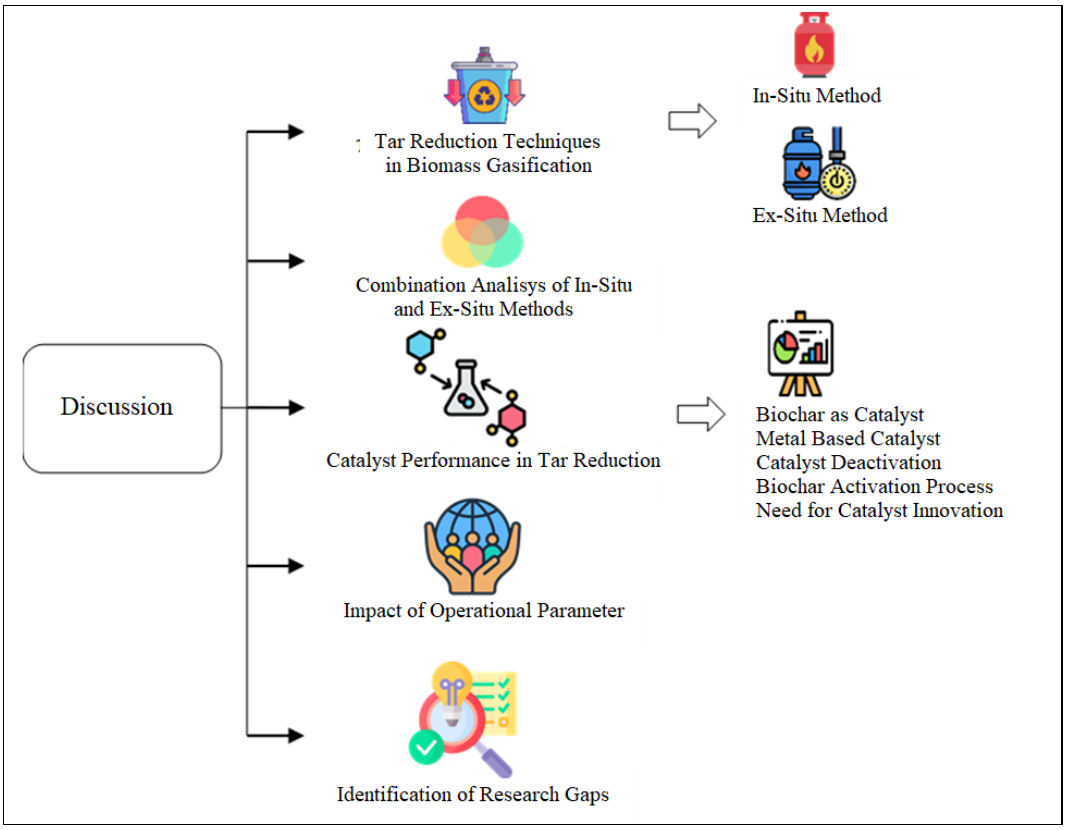

Figure 5. Discussion flow

3.1. Tar Reduction Method in Biomass Gasification

Tar reduction methods in biomass gasification were divided into two main categories, which included in-situ and ex-situ.

3.1.1. In-Situ Method

The in-situ method was conducted directly in the gasifier, typically by modifying the gasifier design and adjusting operational parameters. According to Jayanarasimhan et al. [27], the downdraft-type gasifier produced the lowest tar (0.01–0.5 g/m³) compared to fluidized bed type (5–40 g/m³). This difference was attributed to the high-temperature zone in the downdraft gasifier that facilitated natural tar cracking. Similarly, Zhao et al. [28] found that a three-stage gasifier design with tangential air injection at a 30° angle effectively reduced tar to 99 mg/Nm³ and enhanced gasification efficiency to 76.77%. Numerous in-situ methods used during gasification process showed significant effectiveness in enhancing reaction efficiency, reducing tar formation, and improving the quality of gas products. Furthermore, Thorin et al. [30] used Photofragmentation Tunable Diode Laser Spectroscopy (PF-TDLAS) method to monitor potassium species in real-time during gasification process, providing enhanced process control capabilities.

Sepman et al. [31] introduced Tunable Diode Laser Absorption Spectroscopy (TDLAS), which achieved CO and H_2 conversion efficiencies of up to 99%. This method ensured dynamic monitoring of gas composition inside the reactor, improving the understanding of in-situ chemical dynamics. Similarly, Lee et al. [8] developed a supercritical water gasification (SCWG) process with in-situ production of nanocatalysts. This process successfully increased hydrogen selectivity to 18.8%, while simultaneously reducing the operating temperature and minimizing catalyst deactivation. Wang et al. [32] used in-situ Raman spectroscopy to observe the structural changes of biochar during CO_2 gasification process. The result described the role of K and Ca-based catalysts in enhancing biochar reactivity and gasification efficiency. Additionally, Parvez et al. [6] adopted Sorption-Enhanced Gasification (SEG) technology, which comprised the use of CaO to capture CO_2 in-situ. This method produced hydrogen-rich syngas (>70% vol) with reduced tar content.

In-situ method increased the effectiveness of converting raw materials into premium gas products. Additionally, it incorporated environmentally friendly technologies such as carbon capture, which played a crucial role in minimizing the environmental impact of gasification process. This analysis explained the importance of developing innovative in-situ method to provide highly efficient sustainable energy solutions [33]–[37]. **Table 1** shows a comparative overview of the findings from in-situ investigation.

Table 1. Comparison of in-situ results

Refs	Method	Efficiency	Superiority
[27]	Use of downdraft type gasifier	Low tar (0.01–0.5 g/m³)	Simple and produces the lowest tar among other gasifier types.
[28]	Three-stage gasifier design with tangential air injection	Tar yield: 99 mg/Nm³; Efisiensi gasifikasi: 76,77%	Even temperature distribution; cracking tar is more efficient
[30]	Photofragmentation Tunable Diode Laser Spectroscopy (PF-TDLAS)	High accuracy in real-time measurement of potassium species in gasification	Enables monitoring of potassium-based reactions that influence tar reduction and char reactivity, enhancing process control.
[31]	Tunable Diode Laser Absorption Spectroscopy (TDLAS)	99% CO and H_2 conversion efficiency	Provides real-time monitoring of gas composition inside reactors, improving the understanding of in-situ chemical dynamics during gasification.
[8]	Supercritical Water Gasification (SCWG)	Hydrogen selectivity up to 18.8%	Combines partial oxidation and in-situ nano-catalyst synthesis to enhance hydrogen yield while reducing process temperature and catalyst deactivation.
[32]	In-situ Raman Spectroscopy	Enhanced reactivity with K and Ca catalyst	Monitors real-time structural evolution of biochar, showing catalytic effects that improve reactivity and efficiency in CO_2 gasification processes.
[6]	Sorption-Enhanced Gasification (SEG)	H2-rich syngas (>70 vol%) with reduced tar	Integrates in-situ CO_2 capture using CaO-based sorbents, enhancing hydrogen production and enabling carbon capture for lower emissions.

3.1.2. Ex-Situ Method

Syngas were processed using ex-situ method after leaving the gasifier. Consequently, high tar reduction efficiency was achieved through thermal cracking, plasma technology, and catalytic reforming. Ex-situ gasification method showed significant potential for improving the effectiveness of converting solid fuels into useful gases while resolving several environmental and technical issues. Bielowicz et al. [38] examined ex-situ lignite gasification and found variations in carbon residue transformation influenced by temperature, providing important insights for optimizing reactor design. Similarly, Wiatowski et al. [39] demonstrated that increasing pressure to 0.5 MPa significantly improved the calorific value of gas and methane production, making it an effective method for hard coal. Kapusta et al. [40] reported an energy efficiency of 59% in the oxygen-blown gasification of high-moisture lignite, proving the feasibility of this method for processing lignite, which was typically difficult to use.

From an environmental perspective, Ütnü et al. [41] showed a significant reduction in polycyclic aromatic hydrocarbon (PAH) content in char residue to 2,758 mg/kg compared to 7,159 mg/kg in raw lignite. These findings explained the significant benefits of reducing the risk of groundwater contamination. It was concluded that ex-situ gasification method improved energy conversion efficiency and enhanced environmental sustainability by reducing organic pollutants. These methods laid the foundation for developing more environmentally friendly and efficient gasification technologies. A comparison of ex-situ study results could be seen in **Table 2**.

Table 2. Comparison of ex-situ results

Refs	Method	Efficiency	Superiority
[17]	Use of biochar activated with steam/CO_2.	Tar reduction >90% at 800 °C.	Biochar is an economical and environmentally friendly option because it can be produced directly from biomass and shows increased efficiency after the activation process.
[38]	Ex-situ gasification of lignite	Demonstrated high variability in carbon residue transformation.	Provides insights into temperature-driven changes in petrographic composition, aiding in reactor design optimization.
[39]	Pressurized ex-situ gasification of hard coal	Improved calorific value of syngas with elevated pressures (0.5 MPa).	Demonstrates that pressure significantly enhances methane production and the calorific value of gas products.
[40]	Ex-situ simulation of underground lignite gasification	Process energy efficiency of 59%, with an average gas calorific value of 7.2 MJ/Nm^3.	Shows feasibility of oxygen-blown gasification for high-moisture lignite, addressing challenges of low-rank coal utilization.
[41]	Polycyclic aromatic hydrocarbon (PAH) analysis	Reduction of PAH content in char residue to 2.758 mg/kg compared to 7.159 mg/kg in raw lignite.	Highlights environmental benefits by lowering organic pollutant content in residues, reducing risks of groundwater contamination.

3.1.3. Combination Analysis of In-Situ and Ex-Situ Methods

The combination of in-situ and ex-situ gasification methods offered an innovative approach to improving the efficiency of solid fuel conversion while addressing the weaknesses of each method. In-situ methods offered the advantages of low operating costs and utilizing hard-to-mine fuel reserves, as gasification was carried out directly at the fuel reserve site. However, the method often produced gas with high tar content and variable quality. Incorporating ex-situ processes enabled further refinement of in-situ gas through catalytic reforming or SEG technology. The process enhanced H_2/CO ratio, reduced tar content, and generated high-quality syngas. According to Parvez et al. [6], ex-situ SEG technology could produce hydrogen-rich syngas (>70% by volume) while simultaneously capturing CO_2 in-situ. In particular, the technology provided dual benefits of improved energy efficiency and reduced carbon emission. Jayanarasimhan et al. [27] produced very low tar using downdraft type gasifier in in-situ due to its design characteristics that promote natural tar cracking. When these results were combined with ex-situ technologies such as biochar-based catalytic reforming developed by Shen and Fu [17], tar removal efficiency increased to over 90% while maintaining the sustainability aspects of the system.

Implementation of the two methods faced challenges, such as increased system complexity and higher energy requirements. Zhao et al. [28] observed that a three-stage gasifier design with tangential air injection effectively promoted the production of high-quality syngas with minimal tar. To manage the residual tar, additional reforming technology would be needed. A study by Kapusta et al. [40] showed an energy efficiency of 59% in oxygen-blown lignite gasification that could be improved through ex-situ gas cleaning. Therefore, the integration of these two methods required a carefully designed approach, including optimization of operational parameters and selection of economical and environmentally friendly catalysts.

The combination of these methods was very flexible in utilizing various types of raw materials, ranging from high-moisture lignite to low-calorie hard coal. Moreover, the heat produced during in-situ process could be used to support the ex-situ process, minimizing reliance on external energy sources. Integrating these approaches significantly improved energy efficiency and environmental sustainability. This synergy held considerable promise as a key solution for the clean energy transition, particularly in tapping into inaccessible fossil fuel reserves. For large-scale implementation, a phased approach was needed to test system efficiency and develop catalyst materials that are more resistant to extreme conditions through small-scale projects. By optimizing technology and system design, the integration of in-situ and ex-situ methods had the potential to transform the global gasification industry.

3.2. Catalyst Performance in Tar Reduction

Catalysts played a crucial role in increasing the effectiveness of biomass gasification operations, particularly in lowering tar formation. Studies showed that different types of catalysts, such as metal-based (nickel, iron) and biochar, had different effectiveness in tar reformation.

3.2.1. Biochar as A Catalyst

Biochar was produced from biomass pyrolysis indicating a great potential as an alternative catalyst. Shen and Fu [17] reported that biochar reduced tar by more than 90% at a temperature of 800 °C. The main advantage of biochar was that it was abundantly available, economical, and environmentally friendly [35], [36]. Additionally, activating biochar with steam or CO_2 increased its surface area and porosity, improving tar reforming efficiency. However, the use of biochar as a catalyst also had limitations, including additional energy required for activation process and its impact on performance due to the composition of the biomass feedstock used. Despite this, biochar offered high flexibility because it could be produced directly from the same biomass feedstock as gasification process, reducing the need for catalyst imports [42], [43].

3.2.2. Metal Based Catalyst

Metal-based catalysts, such as nickel and iron, were widely used due to their high efficiency in tar reforming. According to Han and Kim [29], nickel-based catalysts were able to reduce tar by more than 90% at operating temperatures of 800–900 °C. This high efficiency was attributed to nickel's ability to facilitate tar cracking and methane reforming reactions. However, the main challenge with these catalysts was deactivation caused by carbon fouling, which led to performance degradation and required periodic catalyst replacement or regeneration [6], [8], [18]. Even though iron-based catalysts were slightly less efficient than nickel, they offered the advantages of lower cost and abundant availability. These catalysts were more environmentally friendly as they produced fewer hazardous residues during tar reforming process [44].

In terms of efficiency, nickel-based catalysts excelled with high tar reformation rates. From a sustainability and cost perspective, biochar was exceptional because of its renewable raw material source and the simplicity of the production process. Typically, iron-based catalysts provided a balanced alternative between efficiency and affordability, though further refinement would be needed to enhance effectiveness. Aside from the promising performance of various catalysts, several obstacles still need to be addressed.

3.2.3. Catalyst Deactivation

Catalyst deactivation was one of the significant challenges in biomass gasification technology, particularly in ex-situ processes such as catalytic reforming for tar reduction. In addition, catalyst deactivation referred to the decline in a catalyst's effectiveness to facilitate chemical reactions, directly impacting system efficiency. The key factors contributing to catalyst deactivation include carbon fouling, sintering, catalyst poisoning, and physical abrasion. Carbon fouling refers to the area carbon buildup on the catalyst surface, thereby blocking pores and diminishing the active area. The major problem in carbon fouling was the reduction in lifespan, especially in metal-based catalysts. Another contributing factor was sintering, which comprised the aggregation of catalyst particles at high temperatures, leading to a reduced active surface area. Catalyst poisoning was often caused by contamination from substances such as sulfur, phosphorus, or chlorine present in biomass feedstock. Moreover, physical abrasion was caused by gas turbulence or friction with biomass particles. The formation of a stiff carbon layer (coking) was also a significant cause of catalyst deactivation due to incomplete reactions [6].

Catalyst deactivation could reduce reaction efficiency, increase operating costs due to the need for catalyst regeneration or replacement, and disrupt potential operations such as reactor system blockage. To address the issue of catalyst deactivation, several strategies were formulated. These strategies encompassed the use of more durable catalyst materials, such as biochar or iron-based alternatives, regenerating the catalyst through controlled carbon combustion in an oxygenrich environment, and incorporating promoters such as calcium or magnesium to improve catalytic stability. Reducing the risk of catalyst deactivation required optimizing operational factors, such as maintaining temperatures below the sintering threshold while ensuring sufficient temperatures to prevent coking and pretreating feedstock to reduce impurities. The use of this method could reduce catalyst deactivation and improve the sustainability and efficiency of gasification systems. Further study was needed to develop innovative catalysts that could operate at lower temperatures and exhibit increased resistance to sulfur toxicity and carbon fouling, thereby facilitating the implementation of more efficient and economical gasification technologies [45].

3.2.4. Biochar Activation Process

Improving the characteristics of biochar as a catalyst in biomass gasification, especially regarding tar reduction, required an activation process. The activation aimed to increase the surface area, porosity, and presence of active sites in the biochar, along with various other physical and chemical properties. The three main methods used to achieve this aim were chemical activation, physical activation, or a combination of both. Physical activation comprised heating the biochar to high temperatures, ranging from 700 to 900 °C in the presence of reactive gases such as carbon dioxide (CO_2) or water vapor. This procedure increased the surface area and porosity of the biochar, which were essential for catalytic activity [18].

Chemical activation consisted of impregnating biochar with substances such as phosphoric acid (H_3PO_4) or potassium hydroxide (KOH), and then heating it to high temperatures (400–800 °C). Compared to physical activation, chemical activation created biochar with a higher surface area and more evenly distributed active sites. However, this method required careful handling of the chemicals used. By leveraging the advantages of both strategies, combining these two methods produced the best results. The activation process produced micro and mesoporous structures that aided gas diffusion and added functional groups such as carbonyl (C=O) and hydroxyl (-OH) to serve as active sites. Furthermore, the process increased the surface area of the biochar to hundreds or even thousands of m^2/g. In comparison to metal-based alternatives, Shen and Fu [17] showed that biochar activated with steam or CO_2 reduced tar by over 90% at 800 °C, making it an extremely efficient, economical, and environmentally friendly catalyst.

The biochar activation process faced challenges, which included high energy requirements for physical activation, chemical waste management from chemical activation, and dependence on the composition of biomass raw materials. Therefore, optimizing activation methods and advancing supporting technologies were crucial steps to improve the efficiency and sustainability of biochar as a catalyst in the biomass gasification process. When properly developed, this process could support more effective tar reduction and promote the implementation of more environmentally friendly gasification technology.

3.2.5. Need for Catalyst Innovation

Catalyst innovation would be needed to overcome the operational and technological obstacles arising in biomass gasification, particularly in the tar reduction process. Traditional catalysts, such as iron or nickel, showed promise in improving the efficiency of tar reforming. However, some challenges still existed in the aspect of waste management, high production costs, deactivation from carbon fouling, and catalyst poisoning from sulfur or other substances. To address these issues, catalysts that were more resistant to deactivation, capable of operating efficiently at lower temperatures, and environmentally friendly needed to be innovated. One promising innovation was the use of activated biochar as an alternative to metal-based catalysts. Given its wide accessibility, low cost, and potential for direct production from biomass feedstock, biochar presented significant advantages. Studies showed that activating biochar with CO_2 or steam increased its porosity and surface area, thereby increasing the effectiveness of tar reduction. Furthermore, biochar proved to be a more sustainable option than metal catalysts due to the higher resistance to carbon fouling.

Additional advances comprised the creation of hybrid catalysts that combined the benefits of different catalyst types. To produce materials with increased stability and multifunctionality, biochar was combined with certain metals or minerals [46]. This strategy aimed to enhance performance and extend lifespan through synergistic interactions of different catalysts. Furthermore, the exploration of nanomaterials, such as metal nanoparticles, presented new possibilities for the development of catalysts that could operate effectively at low temperatures and reduce energy consumption [47]. Ecologically sustainable approaches to catalyst production and regeneration were important areas for innovation. Wider applications of catalyst technology were supported by applying waste reduction methods and using renewable feedstocks, which eventually minimized environmental impacts [48]. Catalyst innovation focused on accelerating the transition to sustainable energy technologies while improving the efficiency of gasification process. Further study and development in this area remained essential in order to create catalysts that met the requirements for sustainability, cost-effectiveness, and efficiency.

3.3. Impact of Operational Parameters

Parameters such as operating temperature, air ratio, and feedstock type significantly affected tar reduction efficiency. Zhao et al. [28] showed that using an excess air coefficient (ER) of 0.35 increased the reaction zone temperature, promoting tar cracking. Other studies stated that raw materials with high lignin content produced more tar, making raw material selection a critical factor [49].

3.4. Identification of Research Gaps

Although many methods and catalysts were developed, several challenges were not addressed, such as:

- Catalyst deactivation due to carbon fouling.
- High operational costs of plasma technology.
- Limited development of integrated in-situ and ex-situ methods.

Observation showed that an integrated approach, such as combining in-situ methods with biochar catalysts in the ex-situ stage, had great potential to overcome the identified challenges. These findings strengthened the arguments presented in the introduction and abstract section, stating that an integrated strategy for tar reduction was critical to improving the efficiency of biomass gasification systems. The results of this discussion also showed that developing catalysts with higher resistance to carbon fouling and optimizing gasifier design should be prioritized in the future.

4. Conclusion

In conclusion, biomass gasification was a promising technology that supported the transition to clean energy. However, tar formation remained a significant challenge preventing system efficiency and causing operational problems. This article comprehensively reviewed various tar reduction methods, both in-situ and ex-situ, and analyzed the performance of different catalyst types. In-situ methods, such as gasifier design modification and operational parameter optimization, offered economical solutions to reduce tar formation directly during gasification. Downdraft gasifier designs and three-stage gasifiers with air injection effectively reduced tar levels to a minimum. However, these methods had limitations regarding certain feedstocks and often required a combination of additional technologies for optimal results. Ex-situ methods, including catalytic reforming, thermal cracking, and plasma technology, efficiently handled the remaining tar residue.

Nickel-based and biochar-based catalysts showed some distinct advantages. Specifically, nickel was more efficient in tar conversion, while biochar offered a more environmentally friendly and economical solution. Despite these advantages, challenges such as the deactivation of metal catalysts due to carbon fouling and the high energy requirements for biochar activation still required further attention. The integration of in-situ and ex-situ methods signified a highly promising strategy to address the limitations while enhancing the system's efficiency. Combining optimal gasifier design with biochar catalysts or plasma technology became an innovative solution to significantly reduce tar without sacrificing sustainability and economic efficiency.

Future study should focus on developing catalysts with greater resistance to carbon fouling and the ability to function efficiently at lower temperatures. Additionally, optimizing operational parameters was crucial for seamless integration of in-situ and ex-situ methods. Evolving technologies, such as hybrid catalysis, which combined the strengths of various catalyst types should also be explored. By adopting an integrated and innovative approach, biomass gasification could become a more dependable and sustainable solution for addressing global clean energy demands. This study laid a foundation for further exploration and supported the advancement of next-generation gasification technologies.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

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Additional information – No additional information from the authors.

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