Configuration-Dependent Multi-Parameter Optimization in Biomass Gasification: From Operating Windows to AI-Assisted Control

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Abstract: This mini-review provides a focused overview of configuration-dependent and multi-parameter optimization in biomass gasification systems. Rather than broadly summarizing biomass gasification, it examines how key operating variables, including temperature, equivalence ratio, and steam-to-biomass ratio, interact across different gasifier configurations and influence syngas composition, tar formation, and process efficiency. Major reactor types, including fixed-bed, fluidized-bed, dual fluidized-bed, entrained-flow, and supercritical water gasifiers, show different sensitivities to these parameters because of differences in hydrodynamics, heat transfer, and reaction environments. Based on a comparative assessment of recent studies, the review discusses configuration-specific trends, parameter trade-offs, and the limited transferability of operating conditions between systems. Emerging data-driven approaches, including computational fluid dynamics, machine learning, and hybrid modeling, are also considered in the context of multi-parameter optimization. Although these approaches have shown potential for improving hydrogen yield, carbon conversion, and cold-gas efficiency, their current limitations related to data availability, model generalizability, and industrial implementation are also discussed. Overall, the review indicates a gradual shift from fixed operating windows toward more adaptive and condition-responsive gasification strategies. Future research needs include improved data consistency, integrated multi-parameter optimization, real-time process monitoring, and further evaluation of AI-assisted approaches for scalable biomass gasification systems.

Keywords: biomass gasification; operating parameters; syngas; hydrogen production; CFD

1. Introduction

Biomass gasification has regained attention as a key thermochemical pathway in the transition toward sustainable and low-carbon energy systems [1]. In the search for renewable alternatives for power generation, industrial heat, transportation fuels, and chemical production, biomass provides a carbon-lean and widely available feedstock [2]. Through gasification, solid biomass is converted into synthesis gas (syngas) such as a mixture of H_2, CO, CO_2, CH_4, and light hydrocarbons (Figure 1) by controlled partial oxidation at elevated temperatures [3]. The resulting syngas can be directly utilized in combined heat and power systems or upgraded for downstream applications such as Fischer–Tropsch synthesis, methanol production, and H_2 generation, offering substantial flexibility [4].

Over the past decade, biomass gasification research has evolved from conventional reactor design and empirical parameter optimization toward more integrated and performance-driven approaches. Traditional studies primarily focused on individual gasifier configurations such as fixed-bed (updraft, downdraft), fluidized-bed (bubbling and circulating), dual fluidized-bed (DFB), entrained-flow reactors, and supercritical water gasification (SCWG) and examined the influence of operating parameters including temperature (T), equivalence ratio (ER), and steam-to-biomass ratio (S/B) on syngas composition and efficiency [5,6].
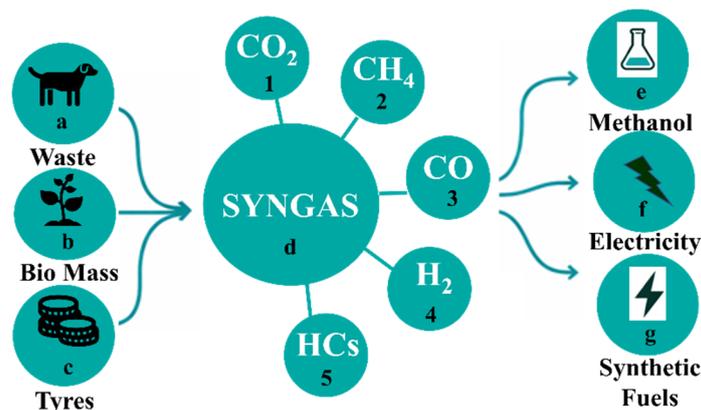
Figure 1. Schematic representation of syngas formation and its downstream conversion pathways from biomass gasification: (**a**–**c**) biomass feedstocks (**a**) animal waste, (**b**) lignocellulosic biomass, and (**c**) organic residues) undergoing thermochemical conversion to produce syngas (**d**); primary syngas components include (**1**) CO_2, (**2**) CH_4, (**3**) CO, (**4**) H_2, and (**5**) light hydrocarbons (HCs). The generated syngas can be further utilized for (**e**) chemical synthesis, (**f**) power generation, and (**g**) energy applications.

In contrast, recent research has shifted toward multi-dimensional optimization and system integration, where operating parameters are treated as interdependent variables governing reactor performance. Increasing emphasis is placed on hydrogen-rich syngas production, driven by the growing demand for clean fuels and decarbonized energy systems. Advanced gasifier configurations such as DFB and supercritical water systems are being actively explored to enhance H_2 yield, reduce nitrogen dilution, and improve carbon conversion efficiency (CCE) [7–9].

Furthermore, the field is transitioning toward data-driven and intelligent gasification systems, where computational fluid dynamics (CFD), machine learning (ML), and hybrid modeling techniques are employed to predict and dynamically optimize operating conditions [10]. These approaches have the potential to enable real-time adjustment of key parameters such as ER and steam input, which may improve process stability and syngas quality. Collectively, these developments indicate a shift from static, configuration-specific studies toward adaptive, configuration-dependent, artificial intelligence (AI)-assisted, and ML gasification strategies. The fundamental reaction pathways and syngas formation routes in biomass gasification are illustrated in Figure 1.

To evaluate the performance of biomass gasification systems under varying conditions, several key performance indicators are commonly used. The quality of the produced syngas, particularly its H_2/CO ratio, lower heating value (LHV), tar content, CCE, and cold-gas efficiency (CGE), is highly sensitive to these operating conditions. Small deviations in ER, T, or steam addition can significantly alter the equilibria of core reactions such as the water–gas shift, Boudouard reaction, steam reforming, and tar cracking, thereby affecting char conversion and overall performance [11].

Despite significant advances, several fundamental challenges persist in biomass gasification research. A critical limitation lies in the absence of a configuration-specific framework that systematically correlates operating windows such as T, ER, and S/B with gasifier design and resulting syngas performance [12]. Existing studies remain highly fragmented, often focusing on individual reactor types or isolated parameters, without enabling cross-comparison across configurations. Consequently, to the best of current knowledge, comprehensive comparative mapping remains limited in its ability to integrate reactor hydrodynamics, operating conditions, and product distribution into a generalized framework, thereby limiting the development of transferable operating strategies and hindering rational system optimization [13].

Furthermore, while recent advances in computational modeling and AI have improved predictive capabilities, their integration with fundamental reactor physics and real-time process control remains limited. Many models still operate under simplified assumptions, restricting their applicability in dynamic and large-scale gasification environments [14].

Finally, challenges related to scalability, process stability, and long-term operation particularly under variable feedstock conditions continue to impede the transition from pilot-scale systems to commercial deployment. These limitations highlight the need for a more systematic and configuration-dependent understanding of biomass gasification operating behavior.

The urgency of addressing this gap is reinforced by the rapid evolution of biomass gasification toward intelligent, AI-assisted, and industrially scalable systems. Recent advances in ML, digital twins, and real-time process control have enabled dynamic optimization of operating conditions, yet the lack of standardized,

configuration-dependent operating frameworks limits their broader applicability [15]. At the same time, increasing demand for hydrogen-rich syngas and carbon-neutral energy systems requires reliable and transferable operating strategies across different gasifier designs. Without a systematic mapping of operating windows, the integration of advanced modeling tools with practical reactor design remains inconsistent, hindering both industrial deployment and cross-study comparability. Therefore, a comprehensive and structured analysis of configuration-dependent operating parameters is both timely and necessary.

In contrast to many existing reviews that focus on individual reactor types or isolated parameter effects, this work provides a structured, configuration-dependent synthesis of operating parameters across biomass gasification systems. By systematically mapping operating windows defined by T, ER, and S/B across major gasifier configurations, this review highlights parameter interactions, trade-offs, and configuration-specific sensitivities that are less consistently addressed in prior studies. In addition, recent advances in computational modeling, ML, and adaptive control strategies are discussed to connect fundamental thermochemical behavior with emerging data-driven optimization approaches. The scope of this mini-review is therefore focused on parameter interactions and configuration-dependent performance, rather than providing a comprehensive overview of all aspects of biomass gasification.

This review is organized as follows. Section 2 describes the literature selection methodology. Section 3 presents the configuration-dependent behavior of major biomass gasifier types and their sensitivity to operating parameters. Section 4 examines the key operating parameters governing gasification performance and their coupled interactions. Section 5 discusses recent advances in dynamic control, reactor optimization, and system integration, along with future research directions. Finally, Section 6 provides concluding remarks and perspectives for the development of efficient and scalable biomass gasification systems.

2. Literature Selection Methodology

This review follows a narrative, non-systematic approach. To ensure transparency and reproducibility, a structured literature selection approach was adopted for this review. Relevant studies were identified using major scientific databases, including Web of Science, Scopus, and Google Scholar. The search was performed using combinations of keywords such as biomass gasification, operating parameters, ER, S/B, gasifier configurations, and AI in gasification.

The review primarily focuses on publications from 2020 to 2026, with particular emphasis on recent advances reported after 2025. Studies were included if they provided quantitative analysis of operating parameters and clearly specified gasifier configurations. Additional selection criteria required the reporting of key performance indicators such as hydrogen yield, CGE, tar content, or CCE. Conversely, studies lacking sufficient experimental or modeling detail, non-peer-reviewed reports, and redundant publications without significant new insights were excluded. The selected literature was then comparatively analyzed to identify configuration-dependent operating trends, which form the basis of the synthesis presented in Tables 1–3 and the subsequent discussion.

A concise literature summary of major biomass gasification operating parameters and their effects across different reactor configurations is presented in Table 1.

Table 1. Literature summary on biomass gasification operating parameters and their effects.

Entry	Gasifier Type/System	Operating Parameters	Key Findings	Ref.
1.	Various (review + modeling)	T, ER, P, steam addition	Higher temperatures increase H_2 and CO and reduce tar and CH_4; higher ER improves conversion but lowers syngas heating value; P shifts products toward CH_4 and CO_2.	[16]
2.	Air-blown BFB (empty fruit bunch biomass)	T; ER	Increasing temperature (800–900 °C) and ER enhanced syngas yield, CGE and carbon conversion, but excessive ER reduced LHV; an intermediate ER gave best trade-off.	[17]
3.	Fixed-bed (thermodynamic model)	ER; fuel moisture; temperature	Model shows that higher ER and lower moisture increase bed temperature and H_2/CO, whereas high moisture (30%) lowers temperature and reduces CO + H_2 in syngas.	[18]
4.	Downdraft fixed-bed	ER; throat ratio; gasifying agent	Lower throat ratio and optimized ER improved gas yield, higher heating value and conversion efficiency; inappropriate throat sizing increased P drop and tar load.	[19]
5.	Air–steam fluidized bed	ER; S/B; temperature	Optimal ER ~0.25–0.30, S/B ~1.5–2.5, and temperature ~800–900 °C improved H_2 yield, tar reduction, and conversion efficiency.	[13]
6.	Steam BFB	Temperature (650–800 °C); S/B = 0.75–2.0	H_2 yield and CGE increased with temperature and S/B up to an optimum; too much steam quenched temperature and reduced carbon conversion.	[20]

Table 1. *Cont.*

Entry	Gasifier Type/System	Operating Parameters	Key Findings	Ref.
7.	Catalytic steam fluidized-bed	Temperature; S/B; in-bed catalyst	Demonstrated H_2-rich syngas (H_2 > 50 vol. %) by combining moderate S/B with Ni-based catalyst; excessive steam or low temperature reduced reforming efficiency.	[21]
8.	DFB steam gasifiers (review)	Bed temperature; S/B; circulating bed material	DFB systems typically operate at 800–900 °C with S/B ≈ 0.5–1.0, producing H_2/CO ≈ 2–3 and H_2 fractions up to >50 vol. %; too low temperature or S/B increases tar and reduces CCE.	[22]
9.	DFB steam gasifier (pilot plant)	Bed temperature; S/B; fuel type	Showed that circulating bed material supplies heat for allothermal steam gasification, enabling N_2-free syngas; higher S/B enhanced H_2 but required sufficient bed temperature to maintain CGE.	[23]
10.	Entrained-flow gasifier (EFG)	Temperature (950–1400 °C); ER; D_p	High temperatures and fine particles (<0.25 mm) gave almost complete conversion, high CGE and very low tar; too low ER led to unconverted char, too high ER reduced LHV.	[24]
11.	Atmospheric entrained-flow	Temperature (950–1100 °C); D_p	Demonstrated that decreasing D_p and increasing temperature improved burnout and reduced tar; coarse particles (>0.5 mm) required longer τ times.	[25]
12.	SCWG, review	T; P; τ; catalysts	For SCWG, typical operating window 500–650 °C and 23–30 MPa; higher temperature and suitable catalysts improve gasification efficiency and H_2 yield, while too short τ increases char/ tar.	[26]
13.	SCWG of lignocellulosic biomass (review)	Temperature; P; biomass composition; catalysts	Reported optimal conditions around 600–700 °C and ~25 MPa with alkaline/metal catalysts; AAEM content in biomass strongly affects gasification rate and gas composition.	[27]
14.	SCWG (systematic review)	Temperature (550–750 °C); P (~25 MPa); feedstock type	Energy efficiencies 20–80% depending on temperature, τ and system integration; wet biomass (sludges, food waste) benefits from SCWG by avoiding drying, but salt precipitation limits operating window.	[28]
15.	Fluidized-bed biomass gasification (review)	Fuel type; ER; temperature; gasifying agent; S/B	Synthesizes that bubbling and circulating fluidized beds (BFB/CFB) gasifiers typically operate at 750–900 °C and ER 0.20–0.30; steam or O_2–steam gasification increases H_2 yield, while air gasification yields lower-LHV syngas with higher N_2 dilution.	[13]

Table 2. Operating windows of major biomass gasifier types.

Entry	Gasifier Type	Temp. (°C)	ER	Moisture (%)	Particle Size (mm)	Pressure (bar)	Tar Level	[Ref.]
1.	Updraft	700–900	0.20–0.35	Up to 35	10–50	1–5	Very high	[29]
2.	Downdraft	850–1050	0.25–0.40	10–20	20–60	1–5	Low	[30]
3.	Cross-draft	1100–1400	0.30–0.45	<15	10–40	1	Very low	[31]
4.	BFB	750–900	0.20–0.35	10–20	0.5–3	1–20	Moderate	[32]
5.	CFB	800–950	0.20–0.30	10–15	0.3–1	1–25	Low	[33]
6.	Entrained Flow	1200–1500	0.16–0.45	<10	<0.2	10–40	Very low	[34]
7.	Dual-Fluidized Bed	800–900	Steam-based	10–20	0.3–1	1	Low	[35]
8.	Plasma	2000–4000	0.05–0.20	Any	Any	1–10	Near zero	[36]

Table 3. Operating parameters of biomass gasifiers and their impact on gasification.

Entry	Parameter	Typical Range	Impact on Gasification	[Ref.]
1.	T	700–1200 °C	Controls tar, H_2/CO, conversion	[16]
2.	P	1–20 bar	Affects syngas composition and throughput	[37]
3.	ER	0.20–0.40	Determines temperature & syngas LHV	[38]
4.	MC	10–20%	Affects energy efficiency & tar	[39]
5.	D_p	0.2–50 mm	Governs reaction rate, bed stability	[16]
6.	Gasifying Medium	Air/O_2/Steam	Dictates H_2/CO ratio & LHV	[40]
7.	τ	1–20 s	Governs carbon conversion	[39]
8.	Gas Velocity (FBG)	0.3–6 m/s	Mixing & carryover	[41]
9.	S/B Ratio	0.3–1.0	Higher H_2 formation	[42]
10.	Bed Material	Sand, dolomite	Tar cracking, heat transfer	[43]

To better interpret the trends presented in Table 1, it is necessary to consider the underlying differences in experimental conditions and reactor configurations. While Table 1 summarizes reported operating parameters and performance metrics across different studies, it is important to note that these values are not directly comparable due to differences in reactor scale, feedstock characteristics, and experimental conditions. Laboratory-scale studies often report higher hydrogen yields and cold gas efficiencies under controlled environments, whereas pilot- and industrial-scale systems are influenced by heat losses, non-uniform flow patterns, and operational constraints [44].

In addition, variations in biomass properties including moisture content (MC), ash composition, and alkali metal content significantly affect reaction kinetics, tar formation, and syngas composition. These factors contribute to the observed discrepancies in reported operating windows across studies [45].

Furthermore, several parameters exhibit competing effects. For example, increasing ER enhances carbon conversion and temperature but reduces syngas heating value due to nitrogen dilution in air-blown systems. Similarly, higher S/B promote hydrogen production through reforming reactions but may reduce reactor temperature and overall efficiency if not properly balanced. These trade-offs highlight the need for careful interpretation of reported data and reinforce the importance of configuration-dependent analysis [46,47].

3. Configuration-Dependent Multi-Parameter Behavior and Optimization

Biomass gasifiers exhibit configuration-dependent behavior due to fundamental differences in hydrodynamics, temperature distribution, residence time (τ), and heat transfer mechanisms [48]. These differences create distinct local reaction environments, which strongly influence syngas composition, tar formation pathways, and CCE. As a result, the sensitivity of key operating parameters such as T, ER, and S/B varies significantly across gasifier configurations [49]. This section provides a configuration-specific analysis of parameter interactions, performance trade-offs, and system-level limitations across major gasifier types.

3.1. Role and Importance of Operating Parameters

Over the past five years, biomass gasification studies have progressed from static parameter tuning toward integrated, multi-variable optimization, linking operating conditions with feedstock variability and real-time system response. Core parameters such as T, ER, S/B ratio, and MC remain fundamental, but their coupled effects are now explored through advanced experimental and computational approaches.

T remains a primary influencing parameter in controlling tar cracking, char reactivity, and syngas composition, yet recent research highlights its interaction with ER and S/B as the main determinant of process energy balance and H_2 yield [50]. Kinetic and CFD-based studies show that controlled variation of ER can stabilize bed temperature and reduce tar formation in fluidized systems without compromising CGE. Likewise, adaptive steam injection strategies have been used to maintain the desired H_2/CO ratio while preventing excessive cooling in DFB gasifiers.

Beyond these core operating variables, feedstock characteristics including D_p, ash chemistry, alkali-metal content, and volatile matter strongly influence gas–solid interactions and local heat transfer. Recent investigations demonstrate that even the modest changes in feedstock morphology or ash composition can alter the optimum ER–S/B window [51]. This sensitivity has motivated the development of feedstock-specific parameter mapping and predictive models based on AI and data analytics. Collectively, these findings suggest that efficient biomass gasification is strongly influenced by the coordinated adjustment of both operational and feedstock parameters to sustain thermal stability, minimize tar formation, and ensure consistent syngas quality across configurations.

In addition to individual parameter effects, recent studies increasingly emphasize the coupled interactions between key operating variables. For example, the interaction between T and ER governs the overall heat balance, where higher ER enhances partial oxidation and stabilizes reactor temperature, while excessive ER leads to nitrogen dilution and reduced syngas quality [52]. Similarly, the interplay between S/B and T critically influences hydrogen production through reforming and water–gas shift reactions, although excessive steam can suppress reactor temperature and reduce CCE [53]. Furthermore, feedstock properties such as MC and D_p introduce additional complexity by altering heat transfer, devolatilization behavior, and gas–solid interactions [54]. These interdependent effects highlight that optimal gasification performance cannot be achieved through single-parameter tuning, but instead requires coordinated multi-parameter optimization tailored to specific reactor configurations and feedstock characteristics.

3.2. Gasifier Configurations and Their Sensitivity to Operating Parameters

Biomass gasifiers differ considerably in hydrodynamics, temperature distribution, τ, and capacity to process various feedstocks. These structural features dictate how strongly each reactor type responds to changes in

operating conditions. Following the framework seen in the reference paper where functional behavior was analyzed by categorizing material classes this section examines the major gasifier types and their characteristic sensitivities to operating parameters [35]. Based on differences in flow regime, heat transfer, and reaction environment, biomass gasifiers can be broadly classified into fixed-bed, fluidized-bed, DFB, and entrained-flow configurations. The representative configurations and their relative positions within thermochemical conversion routes are summarized in Figure 2.
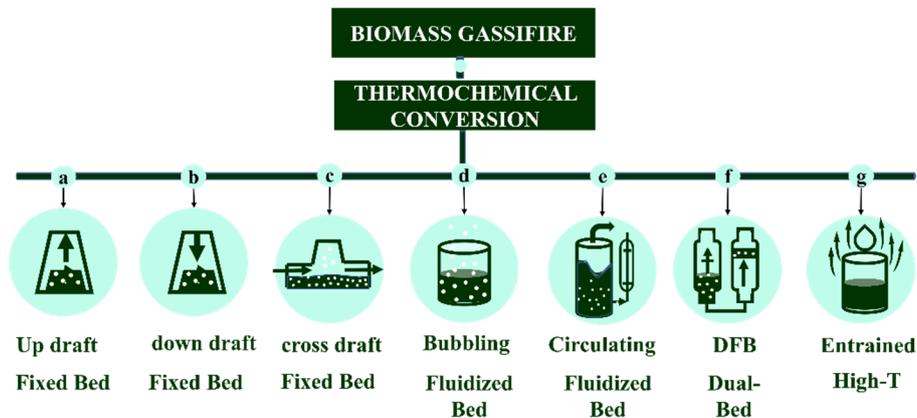
Figure 2. Representative biomass gasifier configurations and their associated operating regimes: (**a**) updraft fixed-bed, (**b**) downdraft fixed-bed, (**c**) cross-draft fixed-bed, (**d**) bubbling fluidized bed, (**e**) circulating fluidized bed, (**f**) dual fluidized bed (DFB), and (**g**) entrained-flow gasifier. Differences in temperature, equivalence ratio (ER), and hydrodynamic characteristics across reactor types are illustrated, emphasizing their role in governing syngas composition, tar formation, and carbon conversion efficiency.

Based on this classification, biomass gasifiers can be categorized into several major configurations according to their flow and thermal characteristics. The typical operating windows and performance characteristics for these configurations are summarized in Table 2.

3.2.1. Fixed-Bed Gasifiers (Updraft, Downdraft)

Fixed-bed gasifiers exhibit distinct sensitivities to operating parameters compared to fluidized and entrained-flow systems, particularly in relation to feedstock properties and flow distribution. Fixed-bed gasifiers, mainly updraft and downdraft types, remain widely used for small- to medium-scale biomass conversion due to their simple structure, reliability, and fuel flexibility. Recent research has focused on improving syngas quality, efficiency, and tar reduction. Unsomsri et al. [55] reported that integrating an updraft gasifier with a cyclonic burner improved air–fuel mixing and high-temperature combustion, resulting in a syngas heating value of 4.32 MJ/Nm^3 with 47% thermal efficiency and over 92% carbon conversion at 815–949 °C. These results demonstrate that efficient air–fuel mixing and high-temperature combustion improve syngas quality and reduce tar, making such systems effective for decentralized power generation. Similarly, Ngamsidhiphongsa et al. [56] optimized a flat-plate downdraft gasifier using CFD modeling and identified an optimal throat-to-gasifier diameter ratio of 0.14 and an air-nozzle height above the throat of 0.125 m, achieving a balance between gasifier efficiency and tar reduction. Ouedraogo et al. [57] suggested that raising the reduction zone temperature from 650 to 1000 °C increased CO and H_2 production and improved cold-gas and carbon conversion efficiencies to over 70% and 95%, respectively.

Although these studies demonstrate significant performance improvements under optimized conditions, fixed-bed gasifiers still exhibit considerable variability in performance depending on reactor design and operating conditions, highlighting several important limitations. While higher temperatures generally improve carbon conversion and reduce tar formation, the extent of improvement varies across studies due to differences in airflow distribution, throat design, and feedstock characteristics. In addition, although optimized downdraft systems report high CGE and CCE, these values are often obtained under controlled conditions and may not directly translate to larger-scale or heterogeneous biomass systems [58].

Compared to fluidized-bed systems, fixed-bed gasifiers exhibit stronger sensitivity to feedstock size, MC, and flow uniformity, which can lead to channeling and incomplete conversion. These limitations highlight the need for improved reactor design and flow control strategies to ensure stable operation and consistent syngas quality. Overall, these findings indicate that fixed-bed gasifier performance is strongly configuration-dependent and less adaptable to variable feedstock conditions compared to fluidized systems.

3.2.2. Bubbling and Circulating Fluidized Beds

Compared to fixed-bed systems, FBG provide improved mixing, heat transfer, and operational flexibility, resulting in more stable temperature control and enhanced adaptability to varying feedstocks. Research on fluidized-bed gasification has evolved from descriptive small-scale experiment toward advanced modeling frameworks and pilot-scale validation aimed at improving syngas quality, tar reforming, and process scalability [49]. Recent studies integrating ML with CFD have demonstrated promising capabilities for predicting gasification performance; however, these results must be interpreted with caution. Reported high accuracies (e.g., $R^2 > 0.95$) are often obtained using relatively limited and system-specific datasets under controlled conditions, which may not be representative of broader operational variability. Many existing models rely on datasets typically containing fewer than several hundred samples and employ internal validation approaches, such as train–test splits or cross-validation, without external validation across independent systems [59].

However, despite these promising modeling advancements, several critical limitations must be considered. Furthermore, the generalizability of these models remains limited, as biomass gasification is highly sensitive to feedstock composition, reactor configuration, and scale. Models trained on specific feedstocks or reactor types may not perform reliably when extrapolated to different operating conditions or industrial-scale systems. Data quality and consistency pose significant challenges. Variations in experimental methodologies, measurement uncertainties, and the lack of standardized datasets introduce additional uncertainty into model predictions. The interpretability of ML models also remains a concern, as many approaches function as black-box predictors without explicitly incorporating reaction kinetics or transport phenomena [60,61].

From an industrial perspective, practical implementation of AI-assisted gasification is still at an early stage. Limitations related to real-time data acquisition, sensor robustness in high-temperature environments, and integration with process control systems must be addressed. Consequently, while ML and hybrid CFD–ML approaches represent a promising direction for dynamic optimization, their current role is better viewed as a complementary tool rather than a standalone solution, requiring further validation and integration with physics-based models. Overall, these findings indicate that FBG offer a balance between performance and operational flexibility, although their effectiveness remains dependent on hydrodynamic stability, data quality, and model generalizability [62,63].

3.2.3. Dual Fluidized-Bed Gasifiers

Among advanced gasifier configurations, DFB systems distinguish themselves by enabling indirect heating and nitrogen-free operation, which significantly enhances hydrogen-rich syngas production. DFB gasifiers have progressed through improved thermodynamic, kinetic, and computational modeling, enabling precise control of syngas composition, temperature distribution, and carbon conversion. Studies show that reactor performance is highly dependent on the S/B ratio and ER. Zhang and Yang [64] demonstrated that at S/B = 0.6 and ER = 0.25, DFB gasification achieved 34.6% H_2, 25.1% CO, 82.3% CGE, and 91.5% carbon conversion. Co-gasification studies further reveal important trade-offs, Nicolucci et al. [65] found that adding 50 wt. % solid recovered fuel increased H_2 concentration to 45% but also raised tar levels by 52%, highlighting the balance between H_2 enhancement and tar control. Castro et al. [66] further refined modeling by integrating a biomass-specific devolatilization model, reducing prediction error below 2% and showing that higher temperatures (750–950 °C) boost H_2 yield while reduce tar by over 30%.

In parallel, sorption-enhanced and chemical looping DFB systems have improved CO_2 capture and H_2 generation. Liu et al. [67] demonstrated a Ca-looping DFB unit with over 80% CO_2 capture and nearly 80% H_2 concentration, operating steadily between 600–900 °C. Dai and Whitty [68] showed that CaO-based sorbents and metal-oxide carriers enable CO_2 separation and air-free oxidation, producing H_2-rich syngas without external air separation or shift reactors. Altogether, these developments highlight DFB gasifiers as flexible and decarbonized systems capable of achieving over 80% CGE, above 90% carbon conversion, and H_2 concentrations up to 80%, underscoring their potential for large-scale H_2 and syngas production from biomass and waste. Collectively, these results suggest that DFB gasifiers provide strong potential for high-efficiency and hydrogen-oriented applications, although their performance is highly sensitive to heat balance, steam input, and system integration.

3.2.4. Entrained-Flow Gasifiers

In contrast to fluidized and fixed-bed systems, EFG operate at significantly higher temperatures and shorter τ, enabling near-complete carbon conversion under controlled conditions. EFG have advanced rapidly in recent years, driven by improvements in feedstock preparation, reactor modeling, and computational validation to enhance feedability and conversion efficiency at industrial scales. Das et al. [44] developed a multi-pore char

gasification model for an EFG using beechwood powder and scaled it to a 605 t/day system. At an ER ratio of 0.2, the model achieved 90% CGE and CCE, with a LHV of 4.5 MJ/kg. Optimal performance occurred with 0.2–0.3 mm particles, balancing conversion and milling energy. Smaller particles and higher inlet P improved conversion, while oxy-steam gasification slightly reduced LHV and CGE but maintained ~90% carbon conversion. These results indicate that advanced CFD models can predict gas–solid interactions, supporting predictive reactor design for large-scale EFG systems.

Feedstock treatment remains crucial for consistent operation. Saha et al. [69] showed that torrefied corn stover reduced pulverization energy by 91% and improved flowability, facilitating stable pneumatic feeding into pressurized gasifiers. Similarly, Santiago et al. [70] found that co-gasifying 20–40 wt. % biomass with refinery residues sustained CGE above 80% and H_2 concentrations over 35%, while mitigating feeding instability. Collectively, advances in modeling, preprocessing, and co-gasification have made entrained-flow systems more predictable, scalable, and efficient, enabling biomass-based operations to achieve over 90% carbon conversion and syngas quality comparable to coal-based configurations.

Despite these advantages, EFGs face several limitations. The requirement for very fine D_ps increases preprocessing energy demand, while high operating temperatures (>1200 °C) impose significant material and energy constraints. In addition, slagging and ash melting behavior can affect reactor stability and long-term operation. These challenges limit their flexibility for heterogeneous biomass feedstocks and highlight the need for optimized feed preparation and thermal management strategies. Overall, EFGs demonstrate high conversion efficiency and low tar production, but their applicability is constrained by high energy requirements, feedstock preprocessing demands, and operational complexity.

3.2.5. Supercritical Water Gasification

Unlike conventional gasification systems, SCWG operates under high-pressure aqueous conditions, allowing direct conversion of wet biomass without the need for drying. SCWG has progressed through advances in catalyst design, H_2 optimization, and reactor engineering under high-P and high-T conditions. According to Liu et al. [71] Ni- and Ru-based catalysts supported on CeO_2, ZrO_2, and Al_2O_3 significantly enhanced H_2 yield and carbon conversion, reaching up to 35 vol. % H_2 and >85% carbon conversion compared with non-catalytic systems. These catalysts promote water–gas shift and methanation reactions while suppressing tar and coke formation. The same authors also cited studies showing that $Ru/CeO_2–Al_2O_3$ catalysts reduced tar by 50–60% and increased total gas yield to 80–90% at 600–700 °C and 25 MPa, indicate the high activity and stability of bifunctional transition-metal catalysts such as Ni and Ru.

Further progress has resulted from improved reactor configurations and integrated modeling. Neves et al. [28] noted that continuous-flow SCWG systems at 600–750 °C and 25–30 MPa achieved >80% gasification efficiency and >35 vol. % H_2 for 5–10 wt. % feed with sub-minute τ. Integration with solid oxide fuel cells (SOFCs), organic Rankine cycles (ORC), or CO_2 capture increased energy recovery and produced H_2/CO_2 ratios above 4.0, indicating near-complete carbon conversion. Experimental work by Thanikodi and Sagade [72] also achieved ~4.7 mol H_2 kg^{-1} feedstock from food-waste mixtures at 400–500 °C and 25–30 MPa. Mechanistic and CFD–Aspen analyses suggested that catalytic SCWG proceeds mainly through water–gas shift, reforming, and methanation pathways. Overall, SCWG is emerging as a H_2-oriented process capable of efficiently converting wet biomass with high gasification efficiency and minimal tar formation, offering clear energetic and environmental advantages over conventional gasifiers.

However, SCWG systems also present important technical challenges. High-pressure operation (≥25 MPa) requires complex reactor design and increases capital cost. In addition, salt precipitation and reactor clogging remain major operational issues, particularly for biomass with high inorganic content. Catalyst deactivation due to sintering, poisoning, and carbon deposition further limits long-term stability. These factors currently restrict large-scale industrial deployment despite the process advantages [73].

In contrast to individual study-based observations, a cross-comparative analysis of different gasifier configurations reveals several consistent and contrasting trends. Fluidized-bed systems typically operate within a narrower ER (≈0.20–0.30), enabling stable temperature control and moderate hydrogen yields, whereas EFGs require higher temperatures (>1200 °C) and exhibit near-complete carbon conversion but at significantly higher energy input. DFB systems demonstrate enhanced hydrogen production due to indirect heating and nitrogen-free operation, although their performance is highly sensitive to S/B and heat balance [74].

However, inconsistencies across studies are evident. For example, while increasing S/B is widely reported to enhance hydrogen yield, several studies indicate that excessive steam reduces reactor temperature and carbon conversion, particularly in systems without sufficient external heat supply. Similarly, the optimal ER range varies

depending on reactor configuration, gasifying medium, and feedstock properties, limiting the direct transferability of reported operating windows [75].

These observations highlight that operating parameters cannot be interpreted independently and must be evaluated within the context of reactor design, hydrodynamics, and feedstock characteristics. The variability across studies also reflects differences in experimental scale, measurement methodologies, and modeling assumptions, which introduce uncertainty in reported performance metrics. Overall, SCWG presents a promising pathway for efficient hydrogen production from wet biomass, although challenges related to high-pressure operation, catalyst stability, and reactor design currently limit its large-scale implementation.

3.3. Key Operating Parameters Governing Gasification Performance

While gasifier configuration defines the reaction environment, overall performance is ultimately governed by a set of interacting operating parameters. In this section, the major parameters influencing biomass gasification are examined in detail, following a structure similar to the material–property framework used in prior reviews. The main operating parameters and their corresponding effects on biomass gasification are summarized in Table 3.

To visualize the key parameters influencing biomass gasification, their typical categories are presented schematically in Figure 3.
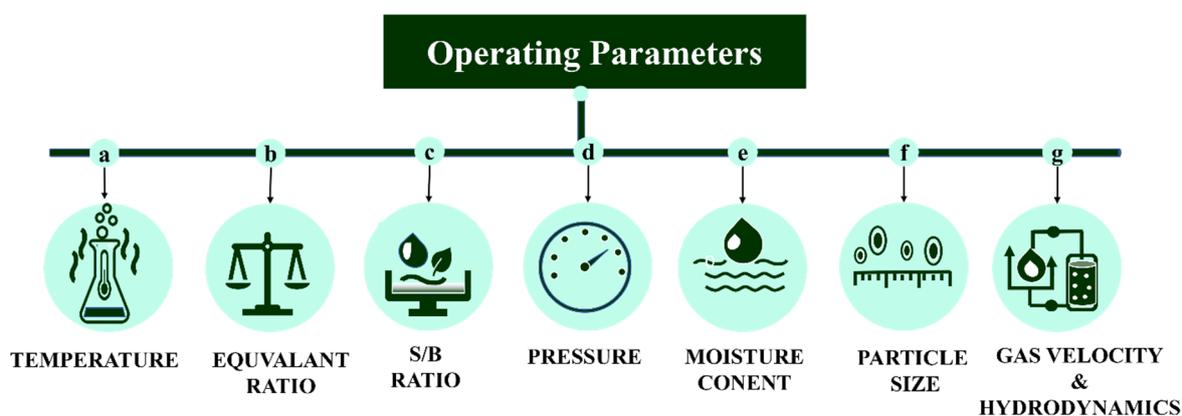
Figure 3. Key operating parameters governing biomass gasification: (**a**) temperature, (**b**) equivalence ratio (ER), (**c**) moisture content (MC), (**d**) residence time (τ), (**e**) steam-to-biomass ratio (S/B), (**f**) particle size (D_P), and (**g**) gasifying medium and reactor conditions. These parameters collectively influence reaction kinetics, heat and mass transfer, tar formation, and syngas composition during thermochemical conversion.

3.3.1. Gasification Temperature

T remains the most influential parameter affecting reaction kinetics, tar reforming, and syngas composition. Recent research has moved beyond empirical optimization toward predictive control using ML, CFD, and kinetic modeling. Sakheta et al. [76] developed a hybrid Aspen Plus–XGBoost model achieving $R^2 = 0.84$–0.94 in predicting gas composition and yields for lignocellulosic gasification. Maintaining 750–900 °C increased H_2 yield by 20–25% and reduced tar by 30–40%, while temperature fluctuations of ±10 °C altered the H_2/CO ratio by up to 0.3, emphasizing the necessity of precise thermal regulation. The same study also demonstrated that hybrid CFD–ML feedback systems maintained temperature uniformity within ±20 °C, suppressed hot spots, and sustained >80% CGE.

Catalyst-driven thermal stabilization has further enhanced temperature control and conversion efficiency. Zhu et al. [9] reported that Ni/ZrO_2, $Rh/Ce–ZrO_2$, and K-promoted biochar catalysts achieved >95 % tar reforming efficiency and H_2 up to 42 vol. % at 800–900 °C. Collectively, ML-assisted modeling, advanced catalysts, and adaptive thermal control have transformed temperature from a fixed operating variable into a tunable design parameter for syngas optimization and reactor stability. However, reported temperature optima vary significantly across studies due to differences in reactor configuration, heat transfer characteristics, and feedstock composition. This variability limits the direct transferability of optimal temperature ranges between gasifier types.

3.3.2. Equivalence Ratio

The ER strongly influences reactor temperature, syngas composition, and tar formation in fluidized-bed biomass gasifiers. Dhrioua et al. [77] developed an Aspen Plus model for Prosopis Juliflora gasification and found

that increasing ER enhances oxidation, raising CO and H_2 yields while suppressing CH_4 and tar. However, excessive ER dilutes the syngas and lowers its heating value. Optimal performance was achieved at an air-to-biomass ratio of 1.0–1.2 (corresponding to an ER of 0.15–0.16) and a T of 800 °C, resulting in a CGE of 69% with minimal tar formation. Lower ER led to incomplete conversion, indicating the need for balanced ER control in efficient gasification systems.

ML studies further suggested ER's strong influence on gas yield and composition. Báez-Barrón et al. [78] trained artificial neural network (ANN) XGBoost, Random Forest, and CatBoost models using 343 datasets, identifying ER as one of the top predictors of H_2, N_2, and total syngas yield. Their models achieved $R^2 > 0.94$, showing that ER between 0.18–0.25 favors higher H_2 (up to 38%), while 0.35–0.40 increases total yield but dilutes gas quality. Dynamic ER control systems using real-time feedback have improved stability and raised carbon conversion above 90%. Altogether, these advances redefine ER from a static setting to a predictive control variable crucial for optimizing efficiency, composition, and reactor performance. Notably, the optimal ER range is highly configuration-dependent and influenced by gasifying medium and reactor hydrodynamics, making generalized operating windows difficult to define across different systems.

3.3.3. Steam-to-Biomass Ratio

The S/B has evolved from a fixed parameter to a key optimization variable influencing H_2 yield, tar reforming, and reactor stability. Zaman et al. [79] used Aspen Plus simulations with response surface methodology to show that an S/B range of 0.7–1.0 balances H_2 yield, CGE, and tar reduction, providing an optimal operating window for small-scale gasifiers. Fang et al. [80] applied ML and Monte Carlo simulations to reveal S/B's nonlinear effects on H_2−C ratios, helping define probabilistic operating envelopes for larger systems.

Recent research has also applied adaptive control and catalytic enhancement. Li et al. demonstrated that real-time S/B adjustment guided by ML models stabilizes syngas composition under varying conditions, while Cihan et al. [81] used Bayesian optimization to fine-tune H_2 yield and tar behavior. Zhu et al. [9] further showed that matching S/B ratios with catalyst activity improves H_2 yield and tar reforming without excessive cooling. Altogether, these studies establish S/B as a dynamic optimization and control parameter essential for maintaining syngas quality and H_2 production across diverse gasification configurations. The effect of S/B ratio also shows conflicting trends across studies, as excessive steam can suppress reactor temperature and reduce carbon conversion, particularly in systems without external heat supply.

3.3.4. Moisture Content

MC has shifted from being a simple constraint to a controllable parameter influencing gasification efficiency and syngas quality. Ongoing studies emphasize reducing the thermal penalty of high-moisture feedstocks through pretreatment and hybrid feed strategies. Peng et al. [82] demonstrated that wet torrefaction pretreatment removes up to 79.8% of alkali and alkaline earth metals (AAEMs) from corn stalks, enhancing reactivity and raising gas heating value to 11.42 MJ/m^3 outperforming conventional torrefaction by improving devolatilization and reducing tar formation. Similarly, Kumar et al. [83] showed that solar drying reduces biomass moisture from 45% to 10–15%, optimizing torrefaction efficiency and lowering CO and particulate emissions while maintaining energy yields above 85%.

In addition, co-gasification of wet and dry biomass has proven effective in offsetting moisture penalties. Studies show that blending sewage sludge with dry residues stabilizes temperature and increases CGE without full dehydration, offering a sustainable route for processing high-moisture wastes. Collectively, advancements in torrefaction, solar drying, and feedstock blending redefine moisture as an active design parameter. Integrated moisture management now improves thermal stability, fuel flexibility, and syngas quality, enabling gasifiers to efficiently handle diverse, high-moisture biomass feedstocks [84].

3.3.5. Particle Size and Biomass Properties

Recent studies have advanced from qualitative observations to quantitative analyses linking biomass particle properties with gasification performance. D_p, ash composition, and AAEMs are now recognized as key factors influencing reactivity, tar conversion, and syngas composition. Ren et al. [85] found that larger particles containing higher AAEM levels exhibit self-catalytic activity, enhancing char gasification and tar cracking while improving carbon conversion despite heat transfer limitations. These findings emphasize the importance of feedstock selection and ash management to exploit natural catalytic effects without external additives.

In parallel, fly ash–based in-situ catalysts have emerged as a sustainable approach to enhance reactivity. Gomes et al. [86] reported that CaO- and Fe_2O_3-rich fly ash improved H_2 yield and reduced tar formation by

promoting water–gas shift and reforming reactions. Computational studies have further clarified that optimal D_p distributions minimize intra-particle heat resistance and improve gas–solid contact, enhancing τ and conversion efficiency. Collectively, integrating D_p control, inherent catalytic activity, and ash composition forms the basis for predictive, feedstock-specific gasification strategies that improve conversion stability and fuel flexibility across diverse biomass resources [87].

3.3.6. Gasifying Medium (Air, Oxygen, Steam)

Modern research on gasifying media has moved from conventional air-based systems toward engineered oxygen–steam and oxygen-enriched environments to boost H_2 yield, reduce nitrogen dilution, and enhance thermal efficiency. Cao et al. [88] used Aspen Plus modeling to compare air, oxygen-enriched air, air/steam, and oxygen–steam gasification. Combining up to 40% oxygen enrichment with steam addition increased H_2 content to 20.4%, halved tar concentration, and improved char conversion, achieving an optimal balance between combustion and reforming reactions.

Wang et al. [13] validated these results in a pilot-scale CFB, finding that an O_2/H_2O ratio of 0.25 at 800 °C produced 43.7% H_2 and over 90% carbon conversion, indicating the potential of oxygen–steam CFB systems for large-scale H_2 production. Similarly, Cao et al. [88] used Aspen Plus modeling to demonstrate that oxygen-enriched air as a gasifying agent improves syngas quality and enhances tar cracking compared with conventional air gasification, suggest that increased oxygen concentration in the oxidant increases the heating value and reduces tar formation. Zhou et al. reviewed biomass gasification in fluidized bed reactors and highlighted that oxygen–steam gasification in CFB systems (e.g., $O_2/H_2O \approx 0.25$ at ~800 °C) significantly enhances syngas quality by increasing H_2 fraction and carbon conversion while reducing nitrogen dilution, reinforcing that gasifying medium ratios are key tunable parameters for optimizing H_2/CO and CGE in industrial CFB gasifiers [89].

3.3.7. Gas Velocity and Hydrodynamics

Gas velocity and hydrodynamics play crucial roles in determining bed expansion, particle dispersion, and reaction uniformity in FBG. Recent advances using coupled CFD–Discrete Element Method simulations have enabled predictive control of gas–solid interactions that govern conversion efficiency and syngas quality. Khodabandehlou et al. [90] applied this approach to a bubbling FBG, finding that optimal gas velocities sustain bed homogeneity and maximize carbon conversion above 90%, while low velocities cause stagnation and incomplete gasification. Banik et al. [91] used CFD– Two-fluid modeling of biomass–coal co-gasification in DFB and found that moderate gas velocity improves gas–solid contact and reforming, while higher flow increases entrainment and heat loss. These modeling advances enable predictive hydrodynamic control for stable, efficient, and H_2-rich FBG.

3.3.8. Quantitative Comparison and Emerging Trends

To further synthesize the findings discussed above, while Tables 1–3 summarize reported operating ranges, a simplified comparative analysis of reported studies indicates common trends. Despite variability in reactor configurations and feedstocks, several consistent patterns have been reported across studies. The optimal ER for maximizing hydrogen yield and CCE generally falls within the range of 0.20–0.30 for fluidized-bed systems, while lower ER values (<0.20) often lead to incomplete conversion. Temperature remains a dominant parameter, with most systems achieving improved syngas quality and reduced tar formation above 800 °C, although the exact optimum depends on reactor configuration.

Similarly, the S/B exhibits a non-linear effect, where moderate values (≈0.5–1.5) enhance hydrogen production, but excessive steam reduces reactor temperature and overall efficiency. These observations indicate that optimal operating windows are not fixed values but instead represent trade-offs between competing effects. To enable cross-comparison, performance trends are better interpreted in a normalized manner based on relative changes rather than absolute values. For example, increasing ER typically improves carbon conversion but reduces syngas heating value, while increasing temperature enhances tar cracking but may increase energy demand. These competing trends highlight the importance of multi-parameter optimization rather than single-variable tuning. Although a full meta-analysis is beyond the scope of this mini-review due to inconsistencies in reported data and experimental conditions, the identified trends provide a basis for semi-quantitative interpretation for understanding configuration-dependent operating behavior.

Nevertheless, the interpretation of these trends is constrained by inconsistencies in experimental conditions, reactor scales, and reporting methodologies across studies. The lack of standardized datasets and uniform performance metrics limits the ability to perform rigorous quantitative comparisons or meta-analysis. As a result,

the identified operating ranges should be interpreted as indicative trends rather than definitive optimal values. Future work should focus on developing standardized reporting frameworks and integrating experimental and modeling data to enable more robust cross-study comparisons.

### 3.3.9. Ash Behavior and Catalyst Deactivation

Ash composition and catalyst stability play a critical role in biomass gasification performance but are often underrepresented in comparative analyses. AAEMs present in biomass can act as natural catalysts, enhancing char reactivity and tar cracking. However, excessive ash content can also lead to slagging, agglomeration, and bed defluidization, particularly in fluidized-bed systems [92].

Catalyst deactivation is another major limitation, especially in catalytic and sorption-enhanced gasification processes. Deactivation mechanisms include sintering, coke deposition, sulfur poisoning, and interaction with mineral matter. These effects reduce catalytic activity over time and impact process stability and efficiency. Addressing these challenges requires improved catalyst design, regeneration strategies, and better control of ash-related interactions [93].

The impact of ash behavior and catalyst deactivation is also strongly configuration-dependent. In fluidized-bed systems, ash-related agglomeration can disrupt bed hydrodynamics and lead to defluidization, particularly under high-temperature and high-alkali conditions. In EFG, ash melting and slag formation influence reactor wall deposition and heat transfer efficiency, affecting long-term operation. Similarly, catalyst stability varies with operating conditions and reactor environments; for instance, high temperatures and steam-rich atmospheres can accelerate sintering and structural degradation, while sulfur and chlorine compounds in biomass contribute to catalyst poisoning. These challenges underscore the importance of integrating ash management strategies and catalyst regeneration approaches into gasifier design and operation, particularly for systems aiming at continuous and large-scale applications.

3.4. Functional Interactions Between Operating Parameters and Gasifier Performance

Recent studies highlight that key operating parameters such as ER, S/B, T, MC, and hydrodynamics (Figure 4) are highly interdependent and must be optimized collectively to achieve efficient, stable, and high-quality gasification. Modern research employs integrated, data-driven models that link these parameters through predictive frameworks rather than treating them in isolation. Ouedraogo et al. [94] demonstrated that hybrid AI models such as Random Forest–Snake Optimization and Layer Recurrent–Particle Swarm Optimization, which can predict nonlinear interactions among ER, S/B, and temperature, accurately identifying optimal conditions for maximizing H_2 yield and minimizing tar formation.
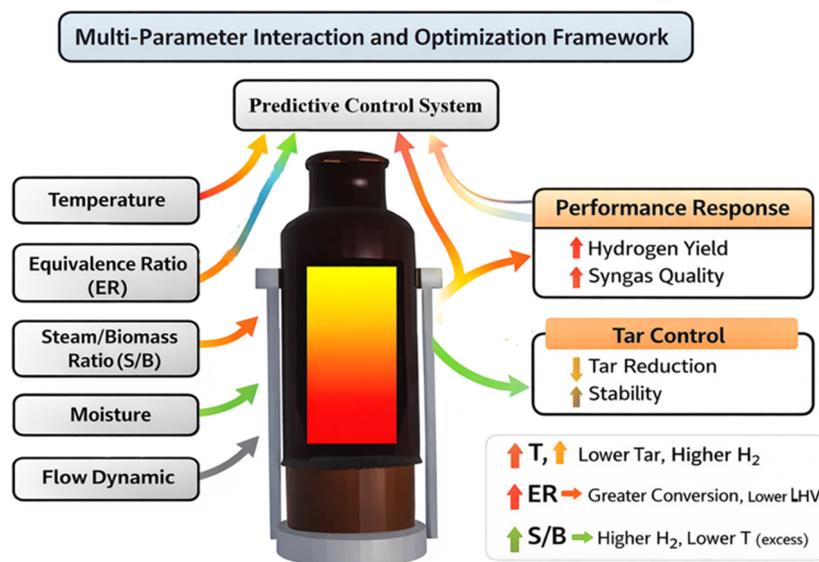
Figure 4. Multi-parameter interaction and optimization framework for biomass gasification, illustrating the role of a predictive control system in dynamically regulating key operating parameters temperature (T), equivalence ratio (ER), steam-to-biomass ratio (S/B), moisture content, and flow dynamics. Arrows indicate the direction of influence and associated trade-offs, highlighting how parameter interactions affect syngas performance (hydrogen yield and syngas quality) and tar behavior (reduction and system stability).

Multi-objective optimization approaches further quantify trade-offs between these interacting parameters. Studies show that moderate oxygen enrichment offsets steam-induced cooling while maintaining high carbon conversion, and that controlled moisture levels stabilize temperature sensitivity. Model Predictive Control systems with real-time sensors now regulate oxidant and steam inputs dynamically, improving syngas consistency and tar suppression. AI-assisted sensitivity analyses have also revealed that fluidized-bed hydrodynamics influence local oxidation and steam reactions, reinforcing the need to co-optimize flow and reaction kinetics. Collectively, these advancements mark a shift from empirical parameter tuning to predictive, integrated optimization, enabling intelligent gasifiers with adaptive control, greater feedstock flexibility, and enhanced scalability for sustainable H_2 and syngas production.

Recent advances in biomass gasification increasingly incorporate data-driven and intelligent optimization strategies, including ML, CFD, digital twins, and adaptive control systems. These approaches have been applied to predict syngas composition, optimize operating parameters, and enhance reactor stability under dynamic conditions. For example, ML models such as ANN, random forest, and gradient boosting algorithms have demonstrated strong predictive capability for hydrogen yield, CCE, and tar formation, particularly when integrated with process simulation tools such as Aspen Plus and CFD models [95].

Despite these advances, several limitations remain. Most ML models are trained on relatively small and system-specific datasets, limiting their generalizability across different reactor configurations and feedstocks. In addition, many models operate as black-box systems without explicit incorporation of reaction kinetics or transport phenomena, reducing their interpretability and reliability in industrial applications. Data inconsistency, variability in experimental methodologies, and the lack of standardized datasets further constrain model accuracy and scalability [96].

Looking forward, future research should focus on the integration of physics-based modeling with data-driven approaches to improve robustness and predictive capability. The development of digital twin frameworks and real-time adaptive control systems is expected to play a key role in enabling dynamic optimization of gasification processes. In addition, the establishment of standardized experimental protocols and large-scale datasets will be critical for advancing ML-based gasification research and facilitating industrial implementation.

4. Future Research Needs and Optimization Directions in Biomass Gasification

Biomass gasification is steadily moving toward more efficient and flexible energy-conversion technologies. Despite significant progress, current systems still struggle to accommodate feedstock variability, maintain stable operating conditions, and deliver consistent syngas quality over extended operating periods. Addressing these challenges will require coordinated advances in reactor design, operating strategies, reaction-zone engineering, and system integration. Rather than isolated improvements, future developments must focus on holistic optimization approaches that link fundamental thermochemical behavior with practical, scalable control strategies. The following subsections outline critical research advancements needed to optimize gasification performance from both scientific and practical perspectives.

In addition to fundamental research challenges, from an industrial perspective, several critical challenges remain in translating laboratory-scale optimization strategies to large-scale deployment. Heat and mass transfer limitations, scale-dependent hydrodynamics, and feedstock heterogeneity introduce significant deviations from controlled experimental conditions. In addition, maintaining stable operation under fluctuating biomass supply requires robust control systems capable of dynamically adjusting operating parameters. Economic considerations, including capital cost, energy efficiency, and integration with downstream processes such as carbon capture and fuel synthesis, further influence the feasibility of large-scale gasification systems. Addressing these challenges requires the development of scalable reactor designs, standardized performance metrics, and integrated modeling frameworks that bridge experimental, computational, and industrial perspectives.

4.1. Advancements in Reactor Design and Operating Parameter Control

Reliable control of operating parameters remains a major challenge in biomass gasification. Variations in feedstock MC, volatile release, and ash composition can destabilize reactor temperature, ER, S/B, and gas velocity, often leading to elevated tar formation and fluctuations in syngas quality. In response, recent research has emphasized reactor designs that promote improved thermal management, enhanced gas–solid contact, and greater operational robustness. Multi-scale and CFD–DEM modeling of industrial-scale systems have improved understanding of hydrodynamics and reaction kinetics, enabling better prediction and stabilization of gasification behavior [97,98]. Fluidized-bed and DFB configurations have demonstrated robust performance in maintaining temperature uniformity and syngas consistency even under variable biomass conditions [99].

Emerging innovations such as staged steam/air injection, bifunctional catalytic materials, and hybrid chemical-looping designs have been shown to minimize tar formation and enhance H_2 yield. Integration of catalytic bed materials and advanced sorption-enhanced reforming processes improves gas purity and thermal efficiency [100,101]. Recent pilot- and industrial-scale demonstrations also highlight the potential of integrating high-temperature reactors and "smart" control systems for adaptive responses to feedstock fluctuations, expanding operational flexibility and energy efficiency [102].

4.2. Advanced Operating Strategies and Interface Thermochemistry

The performance of a gasifier is governed by complex interactions between oxidation, reduction, pyrolysis, and reforming zones, each influenced by temperature gradients, gas composition, and hydrodynamic conditions. The interfaces between these zones are particularly critical, as they control temperature gradients, τ, and local gas composition factors that strongly influence tar formation, carbon conversion, and syngas composition [103]. Studies emphasize that engineering these interfaces through precise control of temperature and τ can substantially enhance reaction uniformity and syngas quality [104].

Advanced operating strategies now focus on catalytic and plasma-assisted reforming at the interface zones to optimize thermochemical conversion. Plasma-enhanced CO_2 reforming has demonstrated improved H_2 and CO selectivity while reducing tar accumulation through enhanced reactive species generation [105]. Likewise, the integration of catalytic reformers within pyrolysis–reduction interfaces enhances CCE and maintains process stability under fluctuating conditions [106]. Such developments illustrate that precise interface thermochemical control, coupled with adaptive operating strategies, can significantly improve syngas composition and overall reactor efficiency.

4.2.1. Transition from Conventional Operating Windows to Dynamic, Condition-Responsive Control

Traditional gasifiers are typically operated under fixed settings for temperature, ER, and gas velocity, despite the fact that optimal conditions vary continuously with feedstock properties and reactor state. Recent advances in monitoring systems featuring real-time tar sensors, in-bed temperature profiling, and micro-gas analyzers enable adaptive adjustment of oxidant flow, steam injection, and oxygen enrichment to maintain stable thermal and reaction environments [98]. In DFB systems, automated adjustment of the S/B ratio and solids circulation rate can effectively mitigate temperature oscillations and stabilize gas composition [107].

Emerging approaches employ ML, digital twins, and predictive control algorithms to anticipate instabilities and optimize reactor conditions in real time [108,109]. Experimental work has also shown that structured and oscillating fluidized-bed regimes can be dynamically tuned for improved flow uniformity and energy efficiency [110]. Such condition-responsive control strategies represent a critical step toward autonomous and resilient biomass gasification systems capable of handling diverse and variable feedstocks.

4.2.2. Reaction-Zone Engineering and Interface-Toughening Approaches

Instabilities in reaction interfaces such as incomplete tar cracking, slag formation, and uneven heat distribution remain significant barriers to achieving high carbon conversion and low tar levels. Engineering sharper thermal gradients controlled cracking zones, and catalytic bed materials can markedly improve reaction conditions. Dolomite- and olivine-based additives have demonstrated major reductions in tar content and improved gas composition in bubbling and circulating fluidized-bed reactors [111,112]. Enhanced solids circulation in DFB systems also improves heat transfer and reaction uniformity through ash–bed material interactions that promote oxygen transport and catalytic reactivity [113,114].

Further advancements in structured bed internals, engineered heat carriers, and catalytic surfaces are expected to enable more precise control of local reaction environments. Understanding catalyst deactivation mechanisms, including coke formation and sintering, is critical for ensuring long-term reactor stability [115]. Moreover, kinetic analyses indicate that dolomite exhibits higher CO_2 gasification efficiency and lower activation energy compared to olivine, making it a promising material for industrial-scale systems [116].

4.2.3. Critical Assessment of Parameter Synergies and Future Outlook

Although the effects of T, ER, S/B, and hydrodynamics have been studied individually, their combined influence leads to complex nonlinear behaviors that remain insufficiently characterized. For instance, steam addition typically enhances H_2 formation but can suppress T unless compensated by an increased ER, while higher T promote tar cracking yet increase slagging risk in high-alkali feedstocks. Kinetic-based modeling indicates that

these parameters interact strongly, influencing gas yield and composition in a nonlinear manner [117]. Hydrodynamics, particularly in fluidized-bed systems, play a dominant role by controlling τ and gas–solid contact efficiency, which amplifies or moderates the effects of thermal and chemical parameters [118].

Future work should focus on developing integrated kinetic–hydrodynamic models and multi-parameter optimization frameworks to better map the coupled effects of operating conditions across biomass types. Such tools combining advanced simulations with data-driven approaches will enhance predictive capability and enable rational tuning of gasifiers for diverse feedstocks and dynamic conditions [119,120].

4.3. Scaling, Integration, and Application-Oriented Optimization of Gasification Systems

Scaling biomass gasification to commercial levels presents challenges in heat transfer, mixing, tar control, and syngas cleanup. Large reactors must maintain stable ER, T, and hydrodynamics while processing diverse feedstocks. Integration with Fischer–Tropsch synthesis, methanol production, and SOFCs requires strict syngas quality management [121,122]

Recent studies show dual and circulating fluidized-bed plants can produce nitrogen-free syngas compatible with fuel synthesis [123]. Coupling gasification with carbon capture and renewable H_2 enhances efficiency and carbon neutrality [124]. Techno-economic analyses and modular designs are key to scalable, decentralized systems, supporting hybrid pathways like solar-assisted or CO_2 hydrogenation-based gasification [125,126].

5. Conclusions

Recent developments in biomass gasification have shifted from a conventional, empirically tuned process into a data-driven, adaptive energy conversion technology. The integration of CFD, AI, and hybrid kinetic–hydrodynamic models enable predictive control of key parameters such as T, ER, S/B, and MC across diverse gasifier configurations. Fixed-bed and fluidized-bed reactors remain effective for decentralized systems, while DFB and supercritical water gasifiers show promise for hydrogen-rich, large-scale applications. The coordinated management of operational parameters, feedstock characteristics, and catalytic enhancement has proven critical to achieving high carbon conversion, low tar, and consistent syngas quality. Future research should prioritize multi-objective optimization, real-time parameter control, and interface thermochemistry engineering to realize robust, high-efficiency, and scalable biomass gasification systems for sustainable energy production. It should be noted that the analytical synthesis presented in this review is limited by the heterogeneity of available data, including variations in reactor scale, feedstock composition, and experimental methodologies. These factors constrain direct quantitative comparison and highlight the need for more standardized and systematically reported studies.

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