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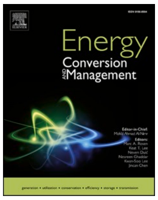

Review Article

Cutting-edge biomass gasification technologies for renewable energy generation and achieving net zero emissions

Farooq Sher [a,*], Saman Hameed [b], Narcisa Smječanin Omerbegović [b,c], Alexander Chupin [d], Irfan Ul Hai [a], Bohong Wang [e], Yew Heng Teoh [f], Magdalena Joka Yildiz [g]

[a] *Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, United Kingdom*
[b] *International Society of Engineering Science and Technology, Nottingham, United Kingdom*
[c] *Department of Chemistry, Faculty of Science, University of Sarajevo, Sarajevo 71000, Bosnia and Herzegovina*
[d] *Peoples' Friendship University of Russia (RUDN University), Moscow 117198, Russia*
[e] *National & Local Joint Engineering Research Center of Harbor Oil & Gas Storage and Transportation Technology /Zhejiang Key Laboratory of Petrochemical Environmental Pollution Control, Zhejiang Ocean University, No.1, Haida South Road, 316022, Zhoushan, PR China*
[f] *School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia, Seri Ampangan, Nibong Tebal, Pulau Pinang 14300, Malaysia*
[g] *Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology, 15-351 Bialystok, Poland*

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ABSTRACT

Biomass gasification is a significant technology for the production of bioenergy. A deeper understanding of biomass gasification is crucial, especially regarding its role in bioenergy carbon capture and storage and its contribution to achieving net-zero emissions. This novel review encompasses gasification processes, novel design technologies, advanced syngas cleaning strategies, scalability challenges, techno-economic analysis, societal and environmental aspects of biomass gasification for achieving net-zero emissions. Biomass gasification typically occurs within temperatures (500 to 1000 °C), pressures (0.98 to 2.94 atm), S/B (0.3–1), residence time (few minutes), moisture content (below 35%) and with or without the presence of a catalyst. It is found that optimizing the gasification key parameters significantly reduces impurities content. Gasifier design affects tar content significantly: updraft gasifiers produce the most tar (about 100 g/Nm^3), downdraft gasifiers the least (around 1 g/Nm^3) and fluidized-bed gasifiers have intermediate levels (around 10 g/Nm^3). Physical-mechanical methods achieve 99% efficiency but reduce energy conversion and generate hazardous waste. Thermal and catalytic cracking methods offer up to 98–100% efficiency, with nickel-based catalysts being highly effective. Biomass gasification has attained a Technology Readiness Level (TRL) of 8–9, demonstrating its feasibility for large-scale implementation. However, it incurs a 15% cost increase and requires additional advancements to address technical and economic challenges. Furthermore, converting syngas into valuable products is vital for achieving negative GHG emissions. Continued research is essential to enhance the overall efficacy of the gasification process. Developing innovative approaches that efficiently valorize all gasification by-products is crucial for enabling widespread adoption in the global market.

1. Introduction

Energy is considered a pivotal part of propelling the encroachment of a nation's economy [1]. Hubbert's peak theory predicts a significant decline in oil resources within 40 years, with oil production possibly dropping to negligible levels by 2055–2060. Current estimates suggest coal may last 130 years, oil 42 years, and natural gas 60 years. Consequently, the imperative to transition from traditional fossil fuels to sustainable substitutes and explore advanced energy possibilities has become pressing. Another pressing environmental concern is the rising levels of atmospheric CO_2, stemming from burning of fossil fuel and contributing to the crisis of climate change [2]. Reducing fossil CO_2 emissions is crucial to achieving climate neutrality by 2050. In 2021, global fossil CO_2 emissions reached 36.4 Gt, a 60% rise from 1990. Substituting conventional fuels with renewables and using carbon capture, utilization, and storage (CCUS) are key strategies to combat climate change. Notably, combining CCUS with biofuel processes, such as biomass gasification for sustainable transport fuels, is gaining significant

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* Corresponding author at: Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham, NG11 8NS, UK.
E-mail address: Farooq.Sher@ntu.ac.uk (F. Sher).

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research interest for its potential to achieve negative carbon emissions [3].

Renewable energy is increasingly accompanied as a key solution to rising worldwide energy demand and GHG emissions. Biomass energy (bioenergy), the merely carbon-based renewable energy, stands out as a potential fossil fuel alternative due to its abundance, diverse applications and reliable energy supply [4]. At present, biomass accounts for approximately 10–14% of the worldwide energy demand and is considered as 4th largest energy reservoir. By 2050, it has the potential to provide around 30% of global primary energy supply. At present, biomass energy generates 2.76 EJ of electricity, accounting for 1.1% of the global electricity source. This share is projected to rise to 5.1% by 2050 [5]. However, its significance is far greater in rural and isolated regions of developing nations, where it fulfils over 90% of the energy needs [6]. Biomaterial is a flexible fuel resource that could be converted into solid, liquid, or form of gaseous by a variety of methods as shown in Fig. 1, contributing to a sustainable generation of energy [7].

Gasification is an auspicious pathway for transforming woody materials into energy forms such as thermal energy, electrical power and diverse vehicular fuels, owing to its enhanced environmental compatibility and superior efficiency compared to burning or pyrolysis [8]. It involves partial oxidation of biomass to escalate the generation of syngas and gain maximum H_2 quantity [9]. Biomass gasification typically occurs within temperatures fluctuating from 500 to 1000 °C and pressures around 0.98 to 2.94 atmospheres, with or without the presence of a catalyst. Various reactor setups, including fixed bed updraft or downdraft, circulating fluidized bed and dual fluidized bed gasifiers, have been utilized for this process [10]. Although the distribution of products relies on a range of factors, including the chemical makeup of the biomass and the gasifying agent used, the primary components of the resulting gas are H_2, CO, CO_2, H_2O, N_2 and CH_4 [11]. Throughout the gasification process, copious by-products emerge, comprising different quantities of fly ash, volatile alkali metals and tar [12]. The generation of tar signifies a diminution in syngas yield, thereby diminishing the operational efficacy of the plant. Furthermore, when temperatures drop below 400 °C, tar condensation can transpire, potentially leading to detrimental effects or operational impediments in downstream processing apparatus. Consequently, it is crucial to either eradicate or mitigate tar formation to optimize process efficiency [13].

Broadly, two principal methodologies exist for the purification of syngas byproducts: (1) in situ abatement and (2) post-gasification treatments aimed at the removal of contaminants from the end product. In-situ elimination involves controlling the process and using additives/catalysts to limit impurities generation inside the gasifier. The extraction entails various physical methods like cyclones, cooling towers/wash columns and electrostatic precipitators [14]. Physical or mechanical techniques entail extracting tar components from the syngas and can be implemented either promptly to hot gas exceeding a temperature of 400 °C (hot gas cleaning) or subsequently chilling the raw gas to temperatures ranging between 19 and 60 °C (wet gas cleaning) [15]. Alternatively, it could undergo chemical treatment via thermal and catalytic cracking, as well as partial oxidation [16]. Heterogeneous

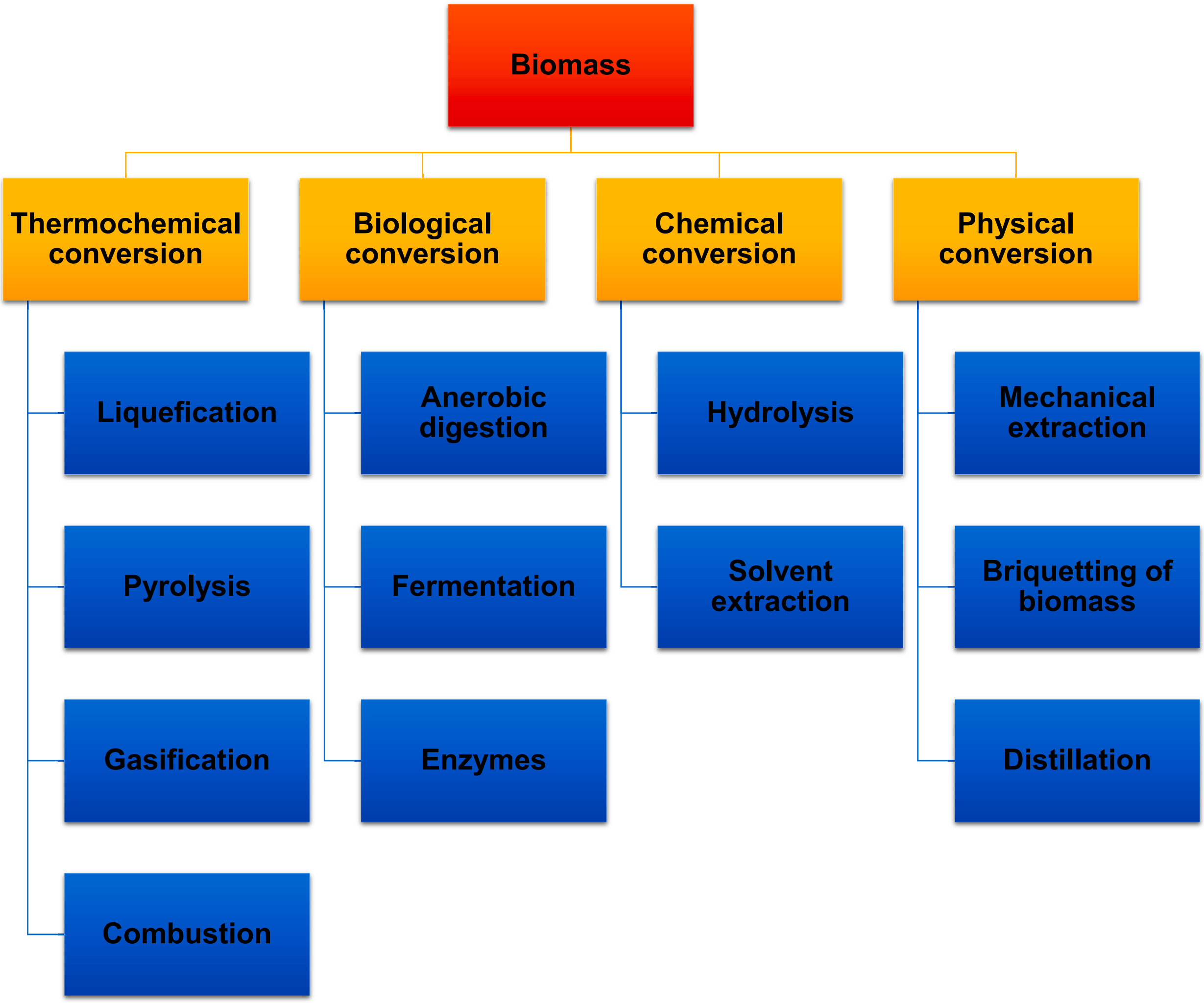

Fig. 1. A detailed overview of biomass-to-energy conversion routes.

thermo-catalysis is pivotal to the commercial viability of biomass conversion, as catalysts mitigate tar and hydrocarbon formation while enhancing reforming. Commonly explored catalysts in biomass gasification include dolomites, alkali metals and supported transition metals, particularly Ni-based variants [17]. Recently, there has been a push towards utilizing plasma technology for the purification of raw syngas, particularly employing nonthermal or low-temperature plasma. These forms of plasma are acknowledged for enabling thermodynamically unfavourable chemical reactions, even under room temperature. This quality makes them appear promising for facilitating energy-efficient chemical conversion [15].

Previous studies provide insight into the gasification process. For instance, Tezer et al. [18] conducted a comprehensive review on biomass gasification for producing hydrogen-rich syngas, comparing and analyzing various gasification models, designs and configurations under different operational conditions. Similarly, Molino et al. [19] evaluated the current state of biomass gasification technologies, discussing their advantages, disadvantages, syngas potential and practical applications. Further, Rios et al. [20], Cortazar et al. [21] and Sikarwar et al. [22] summarized the core aspects of biomass gasification and the main strategies for tar removal. In addition, Faizan et al. [23] and Alptekin et al. [24] provided a critical perspective on catalytic biomass gasification within the review. Zhang et al. [25] further investigated the characteristics of biomass and subsequent char gasification, focusing on feedstock types and their inherent inorganic content. Sansaniwal et al. [6] reviewed the various obstacles to biomass technology, highlighting issues like supply chain management, pretreatment challenges, general limitations, gas conditioning and conversion technologies. Furthermore, Nunes [26] conducted a bibliographic review of the current state of biomass gasification technology. Sansaniwal et al. [27] provided an extensive review of the technical progress and developments in biomass gasification technology, along with the challenges encountered by various stakeholders in its widespread adoption.

Gasification technology has seen significant advancements, with successful implementations at both pilot and industrial scales. A deeper understanding of biomass gasification is crucial, particularly for its role in bioenergy carbon capture and storage (BECCS) and achieving net-zero emissions. This study offers a comprehensive review of the gasification process, detailing its fundamental principles, stages, reactions and the various types of gasifiers used. It thoroughly examines key operational parameters and the production of value-added products during gasification. The study also delves into advanced syngas cleaning techniques, covering both primary and secondary methods. Additionally, a detailed techno-economic analysis of gasification processes and systems is provided, aiding in decision-making to improve overall performance. The societal and environmental impact of biomass gasification is discussed, including a life cycle assessment. Finally, the study highlights the role of biomass gasification in BECCS and the achievement of net zero emission and its potential to address climate change challenges through sustainable bioenergy production.

2. Biomass as sustainable energy source

Biomass is a solitary renewable resource for generating gas and liquid fuels, as well as chemical products [28]. For millennia, biomass has served as humanity's predominant energy source ever since the utilization of fire in ancient times. Fig. 2 illustrates the domestic biomass potential in the EU, which is anticipated to rise from 9.5 EJ/yr in 2015 to 11.2 EJ/yr by 2030. Currently, about 60 % of this ability stem from woodlands, agriculture contributes around 30 % and the remaining 10 % consists of other residues like wood, natural waste and waste oils. While the predictable demand for biomass in the EU is anticipated to remain below its potential, the close approximation consumption potential of domestic woody material is forecasted to escalate from 50% in

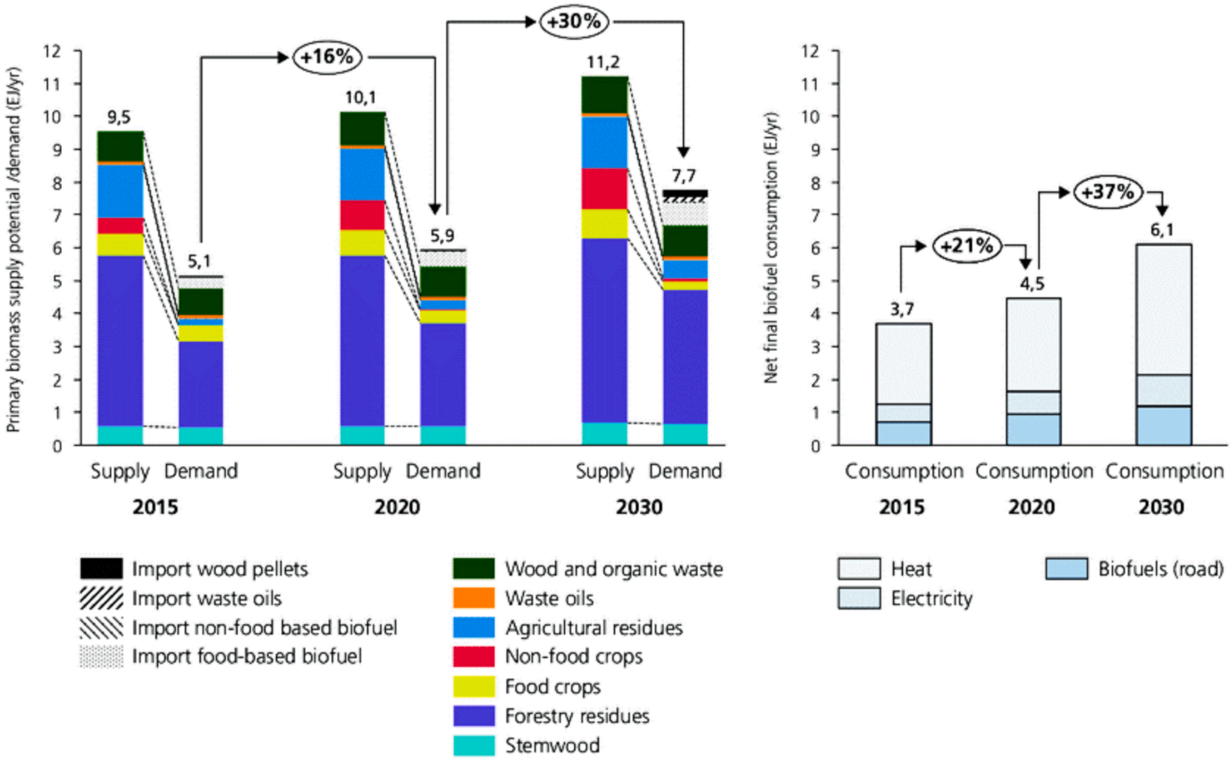

Fig. 2. The projected biomass potential for bioenergy based on data from the Biomass Policies project and the calculated demand for biomass categorized by feedstock type, including imports of solid biomass such as wood pellets, biofuels and used cooking oil sourced from non-EU-28 countries (illustrated in the left panel). The right panel of the figure presents the net final utilization of heat, electricity and road biofuels in the EU-28 for the years 2015, 2020 and 2030, sourced from the S2Biom project [29].

2015 to 60% by 2030, driven by heightened demand across all end-user sectors, including electricity, heat and biofuels for road transport (excluding RJF) [29]. Biomass serves as a renewable energy source that prominently lessens CO_2 emissions, ensures a consistent flame during burning and enhances combustion efficiency. Currently, combustion is accountable for over 97% of global bioenergy generation, making it the simplest and undeviating technology for transforming biomass into valuable energy [30].

Biomass could be sorted based on its origin in biological matter, leading to three primary classifications: natural biomass, waste biomass and dedicated energy crops [31]. Within the waste biomass category, various sources contribute, including agricultural, forestry, marine, industrialized and urban solid residues [32]. Lignocellulose biomass stands as a plentiful, non-edible material primarily sourced from agricultural and forestry residues, encompassing materials like wood chips and rice straw. Agricultural residues have more energy production potential than conventional fossil fuels [33]. This biomass is primarily constituted by varying proportions of cellulose (ranging from 9 to 80%), hemicellulose (comprising 10 to 50%) and lignin (constituting 5 to 35%) [34]. Minor constituents such as lipids, proteins and ash are also present in trace amounts [35]. Biomass which is woody in addition comprises 0.2 to 2.5 wt% inorganic ash ingredients (K, Ca, Na, Si, P and Mg). The gasification relies on the principle that exposing biomass to escalating temperatures causes the fragile C–C (C_1–C_5) chemical bonds to fall apart.

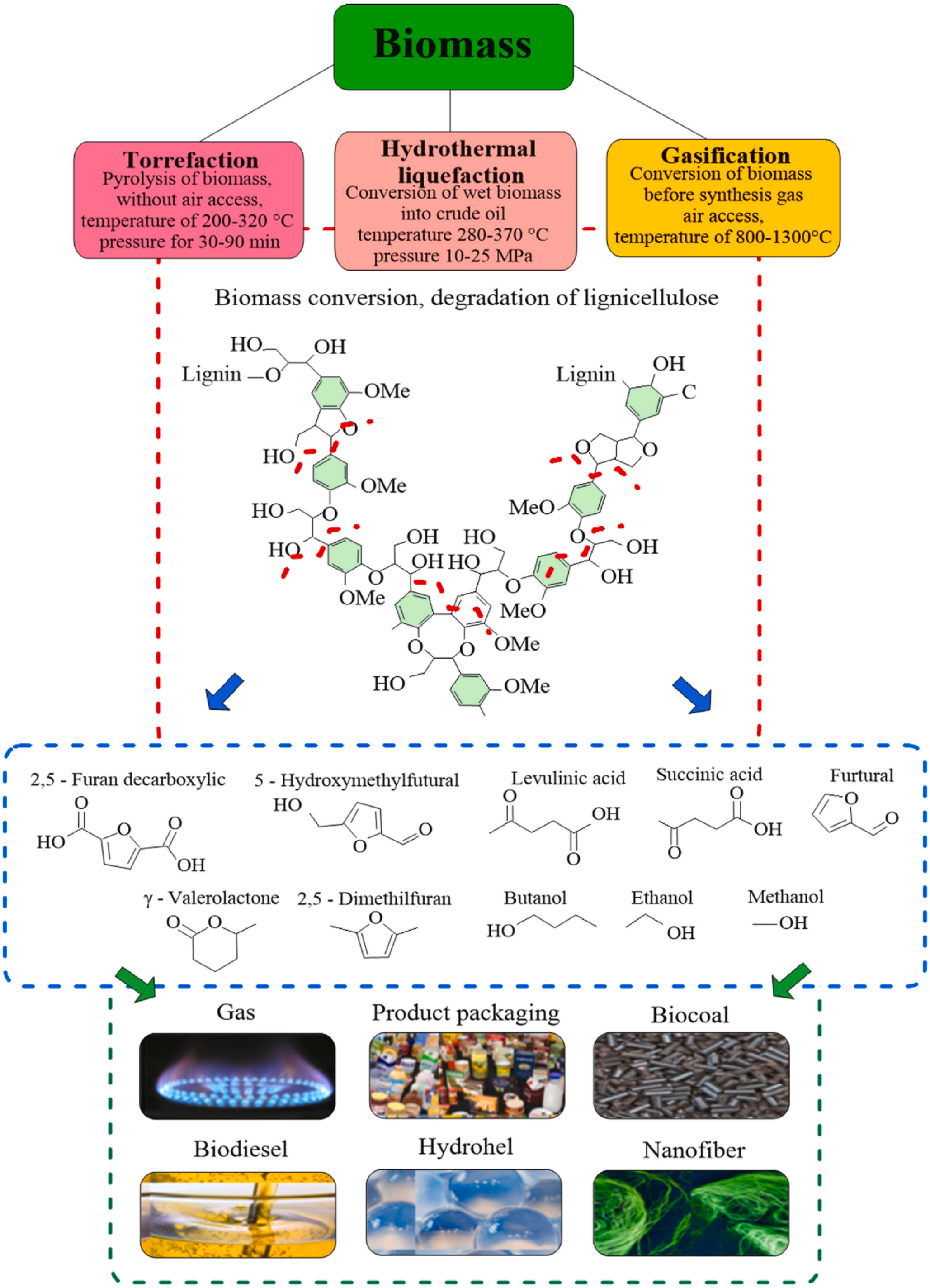

Fig. 3. The foremost constituents of lignocellulosic biomass for conversion of biofuels. Reprinted with permission from [36], Copyright Elsevier ©2023.

This results in the phase of de-functionalization and re-functionalization, ultimately yielding resin, coal and gases. After impurities removal, these products become valuable commodities [36] as shown in Fig. 3.

3. Comprehensive engineering perspective of gasification

Gasification is a pivotal technique for obtaining bioenergy from woody material, with historical roots tracing back to World War II. Gasification is a thermochemical conversion technology [37] that transforms solid or liquid materials into product gas, a versatile ingredient for heat, electrical energy and chemical production [38]. Biomass gasification transforms carbon-rich materials into syngas, predominantly hydrogen and carbon monoxide, along with other gases [39]. It occurs at increased temperatures (800–1100 °C) with a gasifying agent (air, oxygen, steam) at various pressures, up to 33 bar [16]. The gasification process works best for biomass under 35% moisture. For higher moisture levels (25–60%), pre-drying to 10–20% is commended to prevent energy loss in the gasification process. Gasification begins with devolatilization, during which biomass releases vapours and char. Volatiles undergo cracking and reforming, while char undergoes gasification [40]. The resulting gas mix is an intermediate energy source, usable for heat, power through combustion, or synthesis into transportation fuels [15].

3.1. Key steps and influential chemical transformations

Gasification, a notable approach for converting waste into energy, highlights enhanced energy recovery and efficiency in comparison to other methods [18]. Gasification obtains energy by oxidizing biomass in auto-thermal (self-heating) or allo-thermal (external energy input) phases. Auto-thermal gasification involves distinct stages [41]. Gasification key phases encompassing: (1) Oxidation (800–1200 °C, exothermic); (2) Drying (100–150 °C, endothermic); (3) Pyrolysis (300–500 °C, endothermic); (4) Reduction (650–900 °C, endothermic) [42] as shown in Fig. 4. An additional step, tar decomposition captures light hydrocarbons from higher tar compounds [19]. Dry biomass is preferred in gasification due to lower heat requirements. Drying removes moisture through evaporation, typically reducing moisture to around 5% at 200 °C. Typically, biomass is pre-dried to 15–25%, rendering this stage relatively brief compared to others. Pyrolysis breaks down dry biomass, releasing volatiles at 200–700 °C, categorized into primary (200–600 °C) and secondary (>600 °C) pyrolysis [43]. Oxidation is a significant phenomenon that occurs at temperatures exceeding 700 °C, facilitating the conversion of pyrolysis byproducts into CO, CO_2 and H_2O when exposed to oxidizing agents like air, oxygen, or steam [44]. Solid residues are interpreted as char and ashes [45].

Oxidation (combustion) is the exclusive exothermic phase in gasification and generates heat that elevates temperatures to 800–1100 °C. Regulated oxygen levels facilitate the conversion of char, hydrogen and condensable into CO_2 and H_2O. The terminal reduction phase integrates pyrolysis and oxidation byproducts with a gasifying agent to yield the syngas composition. Effective ash removal is imperative to avert char contamination and excessive thermal accumulation [19]. The procedure of gasification initiates with the elimination of moisture, followed by the pyrolysis phase, which transforms biomass into liquid and gaseous products [42]. In Table 1, key gasification reactions are delineated. Homogeneous and heterogeneous reactions encompass oxidation and reduction. Oxidation involves combustible substances reacting with oxygen from biomass. Reduction reactions, occurring at 800–1000 °C, include endothermic (**Eq. (3)** to **(4)**, **Eq. (10)** to **(11)**) and exothermic (**Eq. (5)** and **Eq. (7)**) reactions. Significantly, crucial reactions such as Boudouard, water–gas and steam reforming play a part in the overall endothermic character of reduction reactions [19].

3.2. Critical metrics for effective design and operation

The efficiency and outcome of thermochemical biomass conversion are substantially triggered by diverse process parameters. Operating conditions like pressure, temperature (850–950 °C), S/B (0.3–1), residence time (few minutes) superficial velocity (0.4 to 0.6 m/s for internal combustion engine) and innumerable key considerations impact the transformation of biomass and the production of syngas [50]. The pressure stimulates biochar reactivity, while higher temperatures increase heating rates, creating temperature differences within feedstock particles. Slow heating rates impact gasifier design and product outcomes; lower rates lead to less gas but more tar due to hydrocarbon regeneration. Optimizing the steam-to-biomass ratio (0.3–1) is crucial for maximizing catalytic yield in biomass gasification. The composition of the gas generated is contingent upon the selected gasifying agent, with air being a cost-efficient alternative. Additionally, residence time highly affects both, the formation and tar composition [22]. Another major challenge in catalyst longevity during biomass conversion is deactivation due to carbon deposition, which reduces the active surface area. To combat this, strategies include using basic supports, achieving high metal dispersion and adding promoters [51]. The primary operational factors effecting gasification performance are accessible in Table 2.

Operating a biomass gasification system poses challenges, emphasizing the critical selection of suitable raw materials. Versatility in feedstock enhances energy security and biomass characteristics including chemical makeup, moisture content, volatile matter, particle size and density contribute to syngas composition [24]. Cellulose and hemicellulose affect the nature of gaseous products, whereas lignin

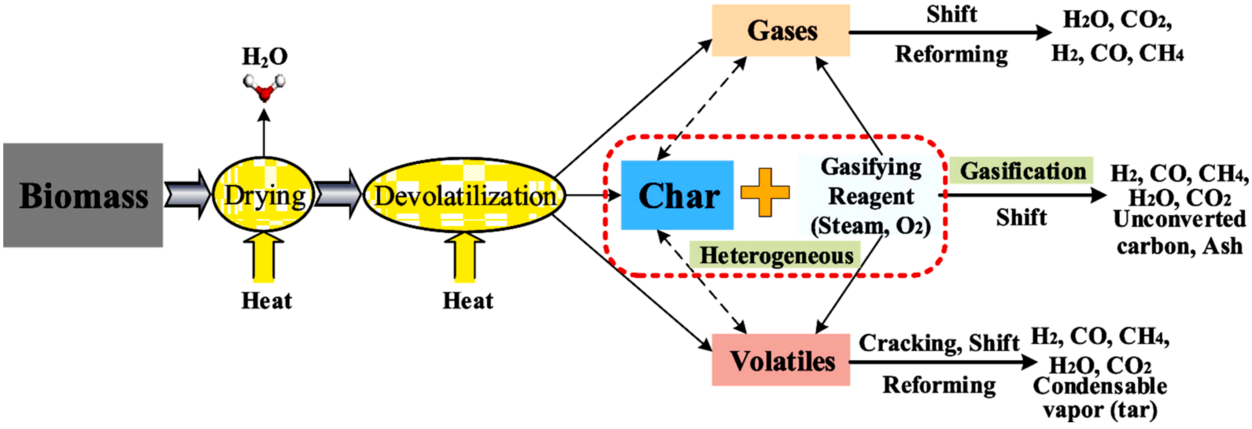

Fig. 4. The key steps of biomass gasification and reaction pathways. Reprinted with permission from [25], Copyright ACS Publications © 2020.

Table 1
The crucial chemical reaction occurs during biomass gasification and the enthalpy of chemical reactions.

	Reaction name	Chemical reaction	Equation number	Nature of reaction	Zone	Enthalpy of reaction (MJ/kmol)	Temperature (^{o}C)	A	E_a	n	A
Heterogenous chemical reaction	Partial combustion	$C + 0.5O_2 \rightleftharpoons CO$	(1)	Exothermic	Oxidation	−111	–	4.34×10^7	1.13×10^8	1	1
	Complete combustion	$C + O \rightarrow CO_2$	(2)	Exothermic	Oxidation	−394	–	–	–	–	–
	Boudouard reaction	$C + CO_2 \rightleftharpoons 2CO$	(3)	Endothermic	Reduction	+172	>700	1.272	1.88×10^8	1	1
	Char reforming	$C + H_2O \rightleftharpoons H_2 + CO$	(4)	Endothermic	Reduction	+131	>700	1.272	1.88×10^8	1	1
	Methanation reaction	$C + 2H_2 \rightleftharpoons CH_4$	(5)	Exothermic	Reduction	−75	300–600	1.368×10^{-3}	6.72×10^7	1	1
	Methane and CO_2 production	$CO + H_2O \rightarrow 0.5CH_4 + 0.5CO_2$	(6)	Exothermic	Reduction	−206	300–600	–	–	–	–
Homogenous chemical reactions	Water-gas shift reaction	$CO + H_2O \rightleftharpoons H_2 + CO_2$	(7)	Exothermic	Reduction	−41	300–600	2.96×10^5	4.74×10^7	1	1
	Partial combustion of CO	$CO + 0.5O_2 \rightarrow CO_2$	(8)	Exothermic	Oxidation	−283	–	5.62×10^{12}	1.33×10^8	0.5	1
	Partial combustion of H_2	$H_2 + 0.5O_2 \rightarrow H_2O$	(9)	Exothermic	Oxidation	−242	–	1.08×10^{12}	1.04×10^9	1	1
	Steam methane reforming	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	(10)	Endothermic	Reduction	+206	>500	3.00×10^5	1.25×10^8	1	1
	Carbon dioxide reforming	$CH_4 + CO_2 \rightarrow 2CO + 3H_2$	(11)	Endothermic	–	+247	–	–	–	–	–
	Methane combustion	$CH_4 + 0.5O_2 \rightarrow CO + 2H_2$	(12)	Exothermic	–	−110	–	3.552×10^{11}	1.305×10^8	1	1
	Partial oxidation of hydrocarbon	$C_n H_m + 0.5O_2 \rightarrow n CO + 0.5mH_2$	(13)	Exothermic	–	Between − 715 and ≈ −2,538	–	1.58×10^{15}	2.026×10^8	1	1
	Steam reforming of hydrocarbon	$C_n H_m + 0{\cdot}.5H_2O \rightarrow n CO + (n + m/2) H_2$	(14)	Endothermic	–	Between + 740 and ≈+2,302	>700	3.00×10^5	1.25×10^8	1	1
	Thermal cracking	$\alpha C_n H_m \rightarrow \beta C_{n\text{-}x} H_{m\text{-}y} + \delta H$	(15)	Exothermic	–	Between − 161 and ≈ −505	–	–	–	–	–
	Dry reforming	$C_n H_m + n CO_2 \rightarrow 2nCO + (x/2) H_2$	(16)	Endothermic	–	Between + 980 and ≈+3,112	–	–	–	–	–
H_2S and NH_3 formation	H_2S formation	$H_2 + S \rightarrow H_2S$	(17)	–	–	–	–	–	–	–	–
	NH_3 formation	$0.5 N_2 + 1.5H_2 \rightleftharpoons NH_3$	(18)	–	–	–	–	–	–	–	–
Reference	[46]	[46]			[47]	[47]	[48]	[49]	[49]	[49]	[49]

influences the generation of tar [52]. Higher cellulose-hemicellulose/lignin ratios in feedstock increase gaseous yields. When biomass moisture content exceeds 30 wt%, it reduces gaseous yield, elevates tar content and necessitates additional energy [24]. Updraft beds oversee up to 60% and downdraft beds tolerate 25 % moisture content; high-moisture biomasses use supercritical water and plasma technology [53]. Reducing particle size facilitates effective heat diffusion, promoting consistent temperatures for reactions. This enhances hydrogen production, carbon conversion, syngas efficiency and minimizes char and tar generation [54]. Fixed beds can manage up to 51 mm, entrained flow requires < 0.15 mm and bubbling beds handle particles up to 6 mm [55]. Biomass with less than 2% ash is suitable for fixed bed updraft gasifiers, while ash exceeding 10% could cause slag. To prevent slag formation, operating a gasifier below the temperature set for ash flow or beyond its melting point is acclaimed [22].

4. Transformative gasification designs for energy challenges

Gasifiers used for converting pre-treated biomass are often termed gasifiers [19]. They vary based on heat source, fluid mechanics, gasifying agent, bed material and operating pressure [59]. Heat supply mechanisms categorize gasifiers into partial oxidation (auto-thermal) and indirect heating (allo-thermal) types [24]. Reactor types include entrained flow, rotary kiln, plasma, fixed bed and fluidized bed reactors [46]. Fixed bed gasifiers comprise three different configurations: updraft, downdraft and cross draft. Similarly, fluidized bed gasifiers have two configurations: circulating and bubbling. Downdraft gasifiers are primarily utilized for power production in smaller power plants and internal combustion engines [60]. Downdraft gasifiers hold the largest market share at approximately 75%, followed by fluidized bed gasifiers at about 20%. Updraft gasifiers and other less common types each contribute around 2.5% to the market distribution [61]. Fig. 5 represents the schematic overview of different biomass gasifiers. Table 3 explains a detailed description of the key specifications, pros and cons of different gasification technologies.

Biomass Chemical Looping Gasification (BCLG) is an advanced syngas production technology [62]. Instead of using molecular oxygen, BCLG employs an oxygen carrier (OC) to oxidize biomass in a fuel

Table 2
The explanatory analysis of critical operational parameters influencing the gasification performance.

Parameters	Observations	Reference
Bed material	Inert medium and potential catalyst. Includes silica, dolomite, olivine and catalysts like Ni and K.	[55]
Gasifying agents	Air, oxygen, steam and CO_2	[22]
Equivalence ratio	Ideal ER: 0.2 to 0.3 for biomass gasification. ER $<$ 0.2 = incomplete gasification. ER $>$ 0.4 = combustion-like process. Lower ER = more H_2, CO in syngas. Higher ER = less H_2, CO, more CO_2, lower heating value.	[56]
Steam to biomass ratio	Optimal SB: 0.3 to 1.0 for biomass gasification. SB 1.35 to 4.04 = more H_2 and CO_2. Fixed bed $>$ fluidized $>$ entrained flow gasifiers for SB capacity.	[57]
Residence time	Longer residence time: ↓ oxygen compounds, ↓ 1–2 ring aromatics, ↑ 3–4 ring aromatics.	[6]
Superficial velocity	Lower velocities = slow pyrolysis, ↑ char, ↑ unburned tars. Higher velocities = fast pyrolysis, ↓ char, ↓ gas residence time, ↓ tar cracking.	[6]
Operating temperature	High gasifier temps = ↑ biomass carbon conversion, ↓ tar, ↑ combustible gases. Typical temp ranges: agricultural waste (750–850 °C), RDF (800–900 °C), woody biomass (850–950 °C).	[55]
Operating pressure	High pressure + larger ER = fewer light hydrocarbons, tar, complete carbon conversion.	[55]
Moisture content	More moisture = slower biomass consumption, impacts pyrolysis, gasifier and product quality. Downdraft gasifiers can handle 40 % moisture, potentially more for updraft.	[6]
Feedstock properties	Biomass contains cellulose, hemicellulose and lignin and moisture content normally contains 10–20 %. Conventional gasifiers use 0.15–51 mm particles. Biomass $<$ 2 % ash = good for fixed bed updraft gasifiers. Ash $>$ 10 % causes slag, especially in downdraft gasification. Operate below ash flow temp or above melting point to reduce slag.	[6,22,53,55]
Carbon deposition	Occurs during catalytic gasification at low temperatures. Specially related to Ni catalyst. Can be lowered by adding another catalyst as a support. Ni can be consumed in combination with other alkali or alkaline earth metals.	[51,58]

reactor, while the reduced OC is re-oxidized in an air reactor as shown in Fig. 6. Transition metal oxides like Fe, Cu, Mn, Ni and Co have been extensively researched as oxygen carriers (OCs) in chemical looping processes [63]. In BCLG, OCs are categorized into synthetic types (including monometallic, oxide mixtures and polymetallic oxides), natural ores (both unmodified and modified) and industrial waste. Inert supports such as Al_2O_3 and SiO_2 are often used to enhance stability, preventing issues like agglomeration, sintering and attrition during repeated redox cycles [64]. The majority of BCLG experiments are conducted in fixed-bed reactors and small-scale bubbling fluidized bed reactors. This method significantly lowers oxygen costs and recycles the heat generated during OC reoxidation to fuel the gasification process [63]. By eliminating the need for a gasifying agent in the CLG process, the overall gasification costs were significantly reduced [65]. Additionally, OCs, typically metal oxides, act as catalysts, reducing tar and carbon deposits [63]. BCLG offers advantages over conventional gasification, including lower emissions, reduced exergy loss [66] and higher quality syngas, positioning it as a promising solution for biomass utilization [63].

5. Competitive biofuels production from gasification end products

Biomass gasification produces three distinct sets of end products: a solid phase, a liquid phase and a gas/vapour phase. Solids (30–50% of input) have non-volatile metals and inorganic elements, liquids (10–20% of input) include oil and tar in smaller amounts and gas (30–60% of input by weight) is like pyrolysis gas but with increased CO_2 content, varying in heating value (3–12 MJ/Nm^3) based on the gasification agent, often oxygen [77]. Ash, the solid phase, encompasses inert materials and minimal unreacted char ($<$1% of ash). Gasification aims to switch carbon into syngas, comprising gases (CO, H_2, CO_2, CH_4, C_2–C_3 compounds) and a condensable phase. In air gasification, the gas phase contains N_2, originating from the atmospheric nitrogen in the air utilized during the process [19]. Syngas, typically at 1–3 Nm^3/kg, with LHV of 4–15 MJ/Nm^3, holds minor components like NH_3, H_2S, HCl and others. These quantities can vary based on gasification technology and operational parameters. Finally, syngas is converted into useful products by a variety of routes like Fischer-Tropsh-synthesis and methanol conversion [47] as depicted in Fig. 7. Gasification technology has attained a Technology Readiness Level (TRL) of 8–9. Similarly, syngas cleaning techniques for internal combustion engines and turbines have extended a TRL of 8–9, whereas for fuel cells, it is still at a TRL of 1–4 [5].

5.1. Insights into tar formation and composition

Tar, resulting from the pyrolysis of lignocellulosic biomass, primarily constituted oxygenated hydrocarbons, condensable hydrocarbons and intricate polyaromatic hydrocarbons [79]. The formation of tar occurs through intricate thermochemical processes such as chemolysis, depolymerization, oxidation, polymerization and cycloaddition. This formation is prompted by various considerations such as the chemical makeup of the biomass, reactor design and operational conditions conducted in gasification [80]. In the realm of gasification, a fixed-bed gasifier yields a lesser quantity of syngas when contrasted with both fluidized-bed and entrained flow gasifiers. While BCLG produces less tar because of the catalytic effect of OCs [63] The estimated weight proportions of primary constituents within tar are as follows: benzene (38%), toluene (24%), single-ring aromatic hydrocarbons (22%), naphthalene (15%), dual-ring aromatic hydrocarbons (13%), heterocyclic compounds (10%), phenolic compounds (7 %), triple-ring aromatic hydrocarbons (6%), quadruple-ring aromatic hydrocarbons (1%), along with additional compounds present in minimal trace quantities [79]. Tar categorization deliberates process conditions and physical properties, leading to primary, secondary, alkyl-tertiary and tertiary condensates [81] as depicted in Fig. 8.

Tar formation in gasification is intricate, commencing with pyrolysis and subsequently involving complex recombination and decomposition mechanisms. The pathways consist of both concurrent and sequential stages, modulated by reaction conditions as given in Fig. 8. The primary tar is created during the initial breakdown of biomass (pyrolysis), comprising acids, sugars, alcohols, ketones, aldehydes, phenols and furans. It is affected by the biomaterial composition [81]. Secondary tar forms as primary tar rearranges processes like dehydration and decarboxylation at temperatures excessive than 500 °C, creating molecules which are heavier like phenols and olefins. Alkyl-tertiary tar comprises constituents such as methyl acenaphthylene, methyl naphthalene, toluene and indene. At temperatures exceeding 800 °C, tertiary tars emerge after the complete transformation of primary tars into secondary tars, with primary and secondary tars not existing concurrently [20]. Tertiary tar comprises condensed tertiary aromatics like benzene, naphthalene, anthracene, phenanthrene and pyrene which form PAHs without additional atoms. These tertiary tars also stem from methyl derivatives of primary tar aromatics [21]. The physical properties

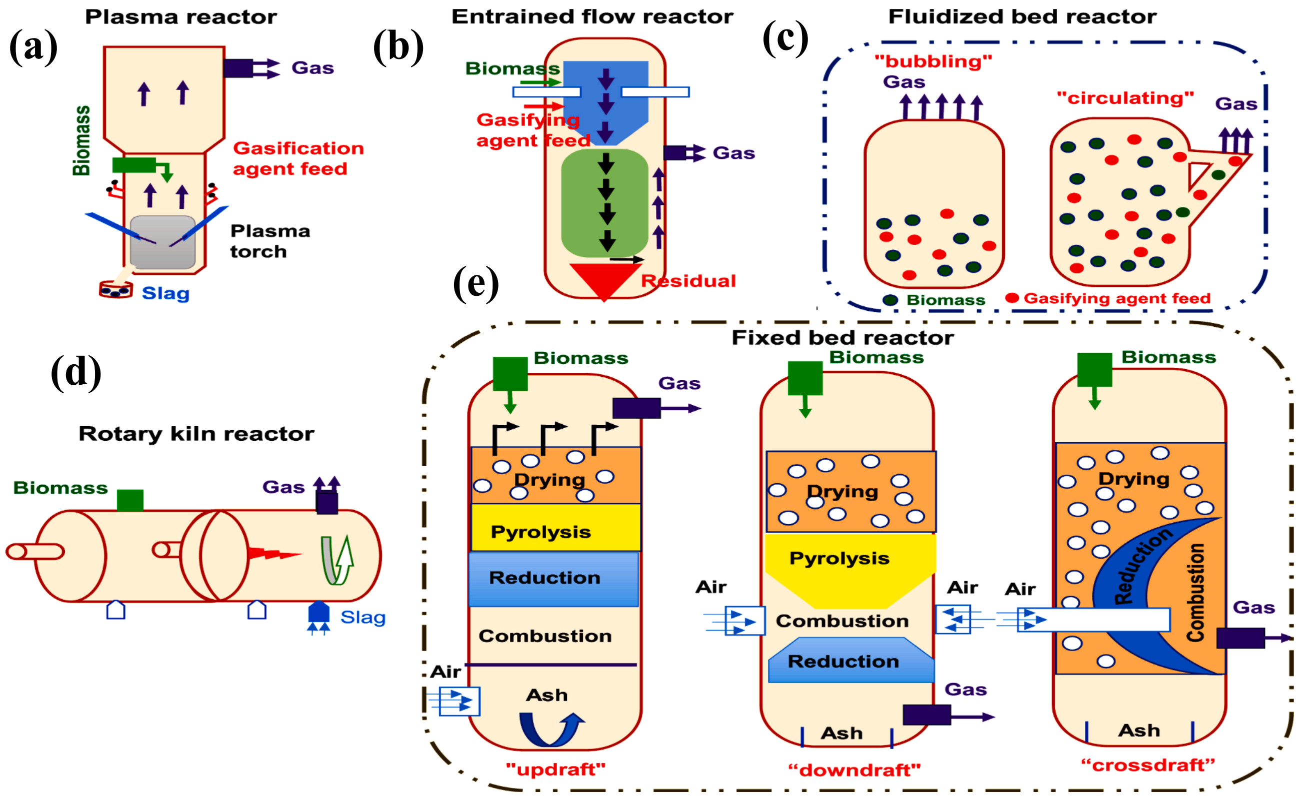

Fig. 5. The schematic view of different gasifier technology. Reproduced with permission from [23], Copyright Elsevier ©2023.

approach examines tar's solubility in water and condensation behaviour.

6. Advanced syngas cleanup techniques

Prior to its utilization in diverse energy applications, syngas must undergo an extensive purification process to eliminate contaminants. Biomass gasification produces a mix of gases, water vapour, tars, H_2S, HCl, NH_3 and other contaminants like particulates and metals [5]. The impurity levels depend on factors such as biomass composition, gasification method, gasifying agents and process circumstances [60]. Eliminating impurities presents a central hurdle within biomass gasification, as it culminates in obstructing and soiling pipelines, heat exchangers and particle filters [82]. To make the syngas suitable for power generation, these impurities must be narrowed to an acceptable value [5] as shown in Table 4. The general categorization of syngas cleaning technologies consists of (1) primary methods, which involve in situ reduction and (2) secondary methods, implemented post-gasification process [81], employing various approaches as depicted in Fig. 9. Primary methods may include strategies such as fine-tuning operational parameters, incorporating catalysts within the reaction bed and altering the gasifier design. Conversely, secondary methods involve procedural techniques such as deploying separation apparatus like scrubbers, cyclones and filters, as well as subjecting tar to post-gasification thermal cracking at high temperatures [83].

6.1. *Primary techniques*

Several determinants critically influence syngas quality, impurity levels and tar generation during the primary gasification procedures. These encompass the gasifier architecture, selection and proportion of gasifying agents relative to feedstock and operational parameters such as temperature, pressure, residence time and catalyst employment [5]. Primary methods are executed during the gasification to hinder impurities creation or transformation within the reactor. The optimal primary approach obviates the necessity for subsequent treatments [20]. The primary focal approaches in biomass gasification involve varying operational parameters (like temperature, gasification agent, pressure, residence time and S/B ratio), distinct attributes of the biomass and the fundamental catalysts harnessed in prior research endeavours [86]. Moreover, advancements in gasification reactor design have resulted in significant benefits, with innovative methodologies being seamlessly incorporated into the reactor architecture to improve impurity removal [21]. Hence, the primary methods include managing the operational conditions, changing the bed material or the utilization of specific catalysts and changing the design of gasifiers [87].

6.1.1. *Effect of operational conditions*

Meticulous management and regulation of operational parameters during biomass gasification are paramount for minimizing or eliminating tar formation in the resultant gas. Numerous essential operational variables profoundly impact gasification efficacy. These encompass temperature, the agent employed for gasification, S/B, ER, residence time, system pressure, biomass variety and moisture content [69]. Table 6 describes the studies conducted on biomass gasification. The process temperature affects both the formation of tar and the production of hydrogen [88]. Cortazar et al. [89] used an olivine catalyst to enhance gasification efficiency in a conical spouted bed reactor. Gasification at 900 °C notably reduced tar concentration to 6.7 g/Nm^3 from 49.2 g/Nm^3 at 800 °C, highlighting temperature's role in tar content. FTIR and GC/MS analyses revealed a temperature-dependent tar formation mechanism, where higher temperatures favoured stable secondary and tertiary tar compounds with greater molecular weights [89]. Tian et al. [90] examined the effects of varying reaction temperatures (700 to 900 °C) on gas composition, LHV, tar concentration, gas volume and the H_2 ratio in the output by utilizing a fluidized bed gasifier to gasify rice husk with a mix of air and steam, employing two distinct bed materials in the process. Remarkably, conducting the gasification at 900 °C

Table 3

The detailed analysis encompasses key operational parameters, advantages and disadvantages of different gasifier technologies [19,27,67–76].

Reactor types	Subtypes	Temperature (°C)	Pressure (bar)	Moisture content	Fuel size (mm)	Capacity	Flows Fuel	Oxidant	Gasification medium	Reactor size (MW_{th})	Tar content (g/NM^2)	Syngas LHV (MJ/NM^2)	Ash content	Applications	Advantages	Disadvantages
Entrained flow reactor		1300–1500	25–30	Low (<15%)	0.15 (only Fine)	Large capacity (60–1000 MW)	Downward	Downward	O_2	30–600	0.01–4	8.8–9.3	Low	Koppers-Totzek Shell coal gasifier Siemens gasifier	Adaptable materials and stable temperatures. Efficient carbon conversion, minimal tar. Rapid reactor turnover for simple control. High-temperature slag formation (vitrified slag). Suitable for widespread implementation.	Requires substantial oxidant. Gas holds ample thermal energy. Efficiency hinges on effective heat recovery. Inefficiency during cold gas phase. High plant and maintenance expenses.
Fixed bed reactor	Updraft	1000	20	High (up to 60%)	5–100	Small (0.01–10 MW)	Downward	Upward	Air	0.1–20	30–150	5.5–6	High	Lurgi (pressurized) Harboøre, Denmark	High thermal efficiency. Manages humidity well. Easy design. Easily scalable. Maximized carbon conversion, minimal tar. Extended solid residence.	Employ mobile grates. Catalysts might need external energy. Possibility of catalyst deactivation. Capacity is limited. Limit reactor scaling for temp control.
	Downdraft			High (up to 25–40%)	20–100		Downward	Downward	Air	<1	0.01–5	4.5–5.5	Low	Viking gasifier (multistage)		
Fluidized bed reactor	Bubbling	800–850	20–60	Varying	6	Medium capacity (1–100 MW)	Upward	Upward	Air/H_2O/O_2	1–50	3.7–62	3.7–8.4	High	Winkler gasifier	Adaptable for load and processing. Ideal for reactive fuels. Minimized tar in syngas. Simple start, stop, and control. Efficient catalyst scaling. Non-mechanical. Highly scalable.	Reduce carbon loss in ashes. Manage dust and ash transport. Maintain low process temperature. Significant capital and maintenance costs. Require size reduction Need specialized materials.
	Circulating			Varying	6		Upward	Upward	Air/H_2O/O_2	20–200	4–20	4.5–1.3	High	Varnamo, Sweden (pressurized)		
Rotary kiln reactor	–	400–1100	–	High (up to 50%)	–	–	Downward	Upward	–	–	–	–	–	–	Minimal impact from composition, humidity, and feed size changes. Highly adaptable loading. Exceptional conversion rates. Suitable for meltable	Temperature control challenges. Moving parts, leakage, and wear concerns. High refractory material consumption.

(*continued on next page*)

Table 3 (*continued*)

Reactor types	Subtypes	Temperature (°C)	Pressure (bar)	Moisture content	Fuel size (mm)	Capacity	Flows Fuel	Oxidant	Gasification medium	Reactor size (MW_{th})	Tar content (g/NM^2)	Syngas LHV (MJ/NM^2)	Ash content	Applications	Advantages	Disadvantages
															waste. Reduced investment costs.	Limited heat exchange. Elevated dust and tar. High maintenance expenses.
Plasma reactor	–	Up to 10,000	1–3	High (up to 40%)	–	–	Horizontal	Horizontal	–	–	–	–	–	–	Inert, non-leachable slag with heavy metals. Reclaim waste for construction. Reduce syngas flow. Minimal pollutants in syngas. Short reaction times. Smooth scaling up.	Nanoparticles in syngas. Refractory material usage. Intermittent processing. Heat shock Need for auxiliary fuel Frequent electrode replacements.

resulted in a significant reduction in tar constituents.

The fuel-to-gasifying agent ratio is pivotal in determining the characteristics of the end products, particularly the tar content. The ER exerts a markedly significant influence on the nature of gasification products, with its effects becoming more pronounced at elevated temperatures [20]. Cao et al. [91] studied different S/B ratios and the research revealed that increasing (S/B) from 0.61 to 2.7 led to an enhancement in the content of H_2, ranging from 16.78 to 19.64 vol%. This improvement was attributed to the facilitation of the water gas shift (WGS) reaction. The study identified an S/B of 1.56 as the optimal ratio, balancing hydrogen concentration while considering cost implications and CO_2 content. In a study by Dhrioua et al. [92] two pyrolysis temperatures (500 and 600 °C) and three particle size fluctuates (0.2 – 0.5, 0.5 – 1 and 1 – 2 mm) were analyzed. The impact of air-to-biomass ratio (0.2 to 1.2) and gasification reactor temperature (800 to 1000 °C) on product gas constituents and tar production (phenol, naphthalene, benzene and toluene) was assessed. Results showed reduced tar production at 600 °C pyrolysis temperature. Smaller particle sizes yielded lower amounts of tar as depicted in Fig. 10.

Gasification agent choice significantly alters gas and tar composition, reaction rate and resulting gas heating value. Steam, air, O_2, CO_2 and their combinations are commonly studied gasification agents [21]. Table 5 provides detailed specifications of these gasifying agents. Air is a cost-effective alternative, despite yielding higher tar concentrations in gasification processes [21]. Air gasification is an exothermic reaction, whereas steam gasification is endothermic and requires an external heat source [93] Limited research has delved into changes in tar composition. Jeremiás et al. [94] found that using a steam combination ended in tar with lesser levels of heavy PAHs in comparison to gasification with air alone. Specifically, the heavy PAH lump content dropped nearly by half, from 11 wt% with air to 6 wt% with O_2/steam gasification. In the study of Jeremiás et al. [94] comparable amounts of heterocycles and light aromatics, approximately 3 wt% for heterocycles and 41 wt% for light aromatics were obtained using a mixture of O_2 and steam, as well as with air. As a result, the proportion of light PAHs was greater in the case of O_2/steam mixture (51 wt%) compared to air gasification (45 wt%). Mojaver et al. [95] conducted a systematic multi-criteria decision analysis, evaluating twenty biomass types and three gasifying mediums. They found that pine sawdust with steam as the gasifying agent performed best, yielding 46.96% hydrogen and only 4.99% carbon dioxide [95].

The gasification process could be executed at either atmospheric pressure or escalating pressure [20]. Mayerhofer et al. [97] indicated that the overall gas pressure leads significantly to the release of primary and secondary tar. Another study highlighted that pressure profoundly affects tar concentration, contingent on the gasifier design. Pressurized operation is advantageous for large-scale processes due to its enhanced thermal transfer efficiency within the bed, which consequently improves gasification performance and mitigates tar production [46]. In an investigation by Tuomi et al. [98] the influence of pressure, fluctuating from 1 to 10 bar, was explored concerning the catalytic activity of several bed materials (sand, dolomite, MgO and olivine) in relation to tar decomposition. The findings revealed that under higher pressures, dolomite and MgO exhibited a marginal decline in their catalytic activity. In contrast, sand and olivine demonstrated an augmentation in catalytic activity with increasing pressure. Consequently, the conversion of tar was boosted in systems utilizing sand and olivine as bed materials.

Gas residence time within a gasifier is pivotal, impacting both the extent and intensity of reactions at a specified temperature. Reduced residence times inhibit tar cracking, thereby diminishing conversion efficiency. Extended residence times facilitate enhanced interactions between tar and the gasifying agent, leading to reduced tar formation and improved process efficacy. Design considerations must therefore accommodate this essential parameter [99]. Fixed bed reactors, particularly downdraft gasifiers, are adept at tar removal due to their prolonged residence times. Conversely, updraft fixed beds generally yield

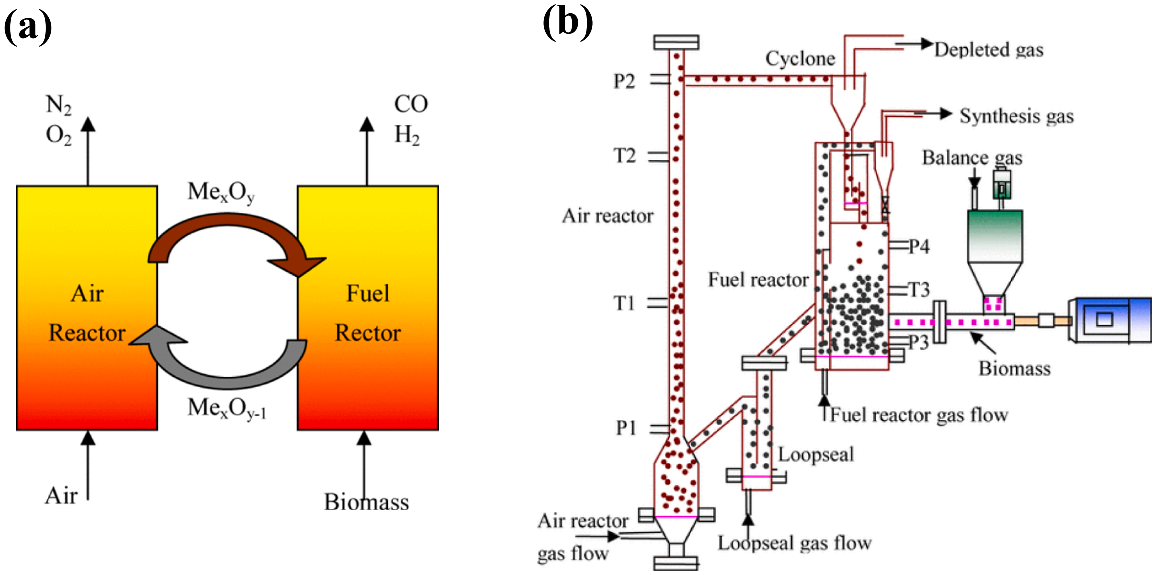

Fig. 6. Schematic representation; (a) Biomass chemical looping gasification (BCLG) and (b) Interconnected circulating fluidized beds for BCLG. Reproduced with permission from [65], Copyright ACS ©2014.

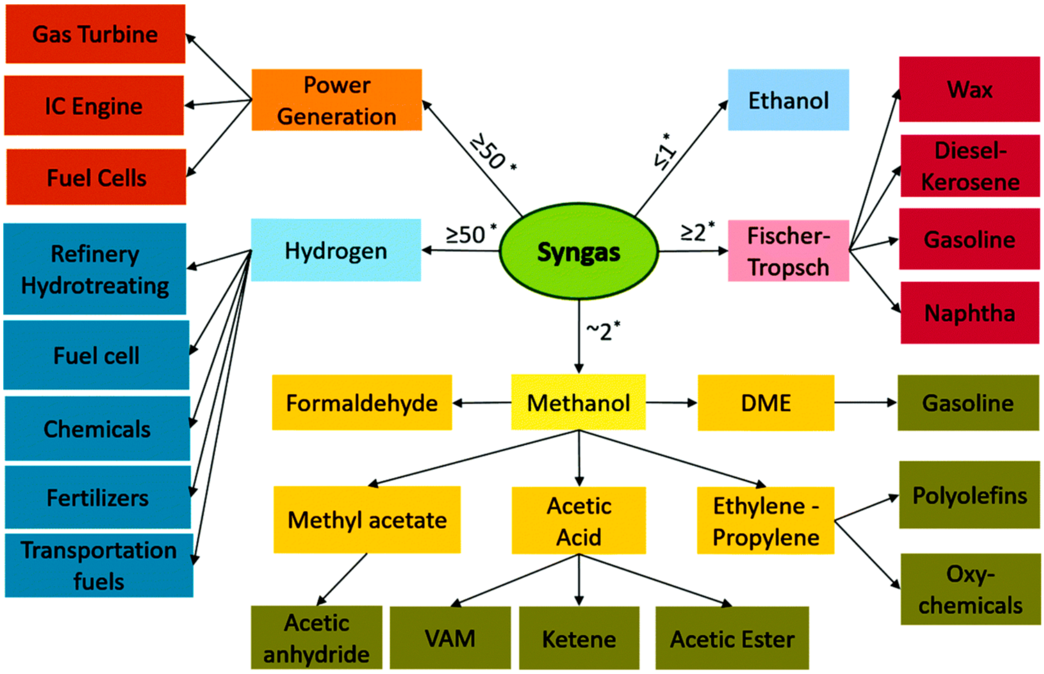

Fig. 7. The transformation of syngas to valuable biofuels by a variety of processes. Reproduced with permission from [78], Copyright RSC ©2017.

gas with elevated tar concentrations. However, fluidized beds exhibit shorter residence times, while entrained bed gasifiers have even briefer residence times, surpassing those of fluidized beds [99]. Park et al. [100] delved into mitigating primary tar vapour by utilizing hot char particles within a fixed bed reactor. They examined a range of residence times, spanning from 0.04 to 0.12 s. The results indicated a notable enhancement, showcasing a reduction in tar content by approximately 25%.

Gasification performance is majorly obstructed by quite a few key biomass characteristics, including its type, particle size and moisture content. The composition of lignocellulosic waste, primarily consisting of cellulose, hemicellulose and lignin, varies depending on the source of the biomass [88]. In general, biomass with elevated lignin content tends to produce higher yields of tar, while those richer in cellulose or carbon content tend to yield lower tar concentrations [22]. Smaller biomass particles, due to their higher surface area per unit mass, facilitate accelerated rates of heat and mass transfer among various phases [88]. Moreover, utilizing smaller particles reduces intraparticle reactions between tar and char, consequently affecting the yields of the resulting products [101]. However, decreasing the biomass particle size to not more than 1 mm results in a sharp rise in energy consumption, accounting for about 10% of the energy output derived from the process of gasification [102].

Biomass moisture content significantly affects the energy balance in the gasification reactor. Woody and specific herbaceous biomass usually have moisture under 15 wt%. However, a biomaterial that is freshly harvested may contain moisture levels as high as 60 wt% [22]. Introducing biomass with high moisture content (exceeding 40 wt%) lowers the gasification temperature, thereby diminishing process efficiency due

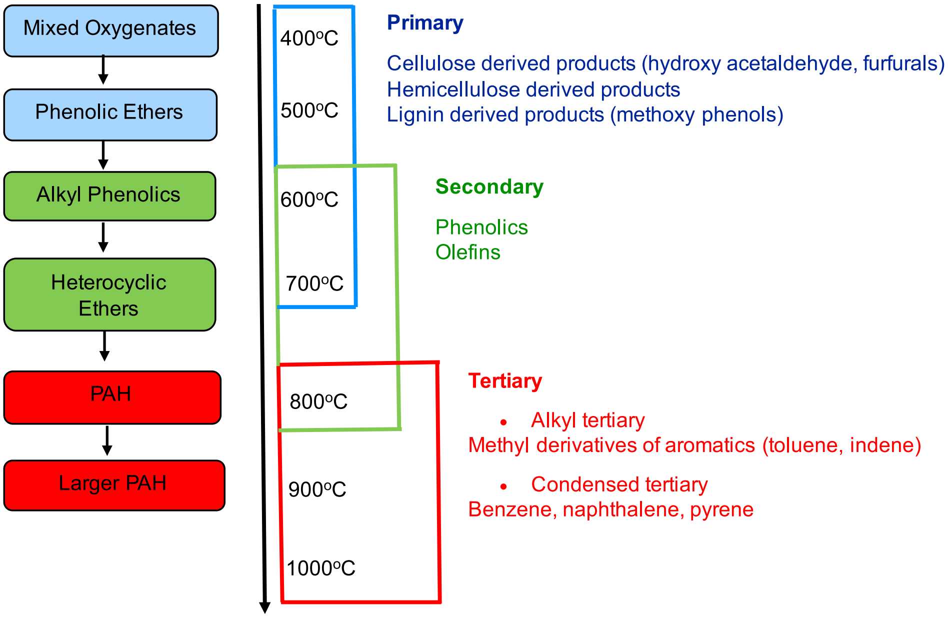

Fig. 8. The classification and formation stages of tar classes from biomass based on temperature.

Table 4
Syngas cleaning requirements for some typical end applications [84,85].

Pollutants	Steam cycle power generation	IC engine	Gas turbine	FT synthesis	Methanol synthesis	Solid oxide fuel cell	Molten carbonate fuel cell	Proton exchange membrane fuel cell
Particulate matter (dust, soot, ash)	Lesser adaptations	< 50 (PM_{10}) mg/Nm^3	<30 mg/Nm^3	<0.5 mg/Nm^3	–	<1 ppmw	<0.01 nm	–
Tars	Lacking worth but condensation must be stopped	< 100 mg/Nm^3	<50 mg/Nm^3	<1 ppmv	<100 ppmv	Many tens to few hundred ppmv	<2000 ppmw	<100 ppmv
Sulphur (H_2S, COS)	Restrained by regulations	Restrained by regulations	<20 ppmv	<0.01 ppmv	<1 mg/Nm^3	Few ppmv	<0.1 ppmv (H_2S)	<1 ppm
Nitrogen (NH_3, HCN)	Restrained by regulations	Restrained by regulations	<50 ppmv	<0.02 ppmv	<0.1 mg	–	<0.1 ppmw (HCN) <1%vol (NH_3)	–
Alkali metals (specifically K and Na)	–	–	<0.02 ppmv	<0.01 ppmv	–	1 ppmv	–	–
Halides (specifically HCl)	–	–	<1 ppmv	<0.01 ppmv	<0.1 mg/Nm^3	Few ppmv	<0.1 ppmw	–
Heavy metals	–	–	–	<0.001 ppmv	–	–	–	–

to the markedly endothermic nature of water evaporation. An additional 2260 kJ of energy is necessitated to evaporate each kilogram of moisture in the biomass. Barco-Burgos et al. [103] biomass with moisture content below 35 wt% is considered appropriate for processing. This balance enables the formation of high-efficiency syngas with reduced tar levels while ensuring cost-effectiveness [103]. Achieving the best performance of the feeder and gasification entails feeding biomass with a content of moisture ranging from 10 to 15 wt%. This range is deemed advantageous due to the benefits conferred by a certain level of moisture in the feed [104]. The gasification performance of local biomasses from West Azerbaijan, including wheat straw, chickpea straw, sunflower seed shells and lentil straw was studied by Mojaver et al. [105]. Among these, chickpea straw produced syngas with the highest concentrations of hydrogen, methane and carbon dioxide across various gasification temperatures and steam-to-biomass ratios.

6.1.2. *Effects of additives*

The efficacy of syngas cleaning was predominantly altered by the quantity of the additive used. Research conducted by multiple investigators regarding the influence of catalysts, such as dolomite, limestone, olivine sand, bauxite, lanthanum, alumina, nickel aluminate, cobalt, natural clay minerals and iron minerals [87]. Guo et al. [126] discovered that employing air–steam as the gasification agent, with a constant temperature of 700 °C, followed by a progressive rise in CO_2 and H_2 contents as the quantity of steam available to the gasifier increased gradually. Furthermore, they observed that elevating the temperature, S/B ratio and dolomite mixing proportion led to a continuous reduction in tar constituents, including light tar, while the concentration of heavy tar comparatively increased as depicted in Fig. 11. Boot-Handford et al. [127] discussed the feasibility of employing calcined limestone and dolomite as primary catalysts for tar cracking in downdraft gasification consuming rice husk. The catalytic impact of the calcined limestone bed was evident at temperatures of 700 °C and 800 °C, resulting in tar conversion rates of 25% and 43%, respectively.

The efficacy of olivine as a catalyst for tar eradication primarily stems from its magnesite (MgO) and iron oxide (Fe_2O_3) contents, with olivine containing notably higher levels of iron oxide compared to dolomite. Studies have indicated that the catalytic efficiency of olivine

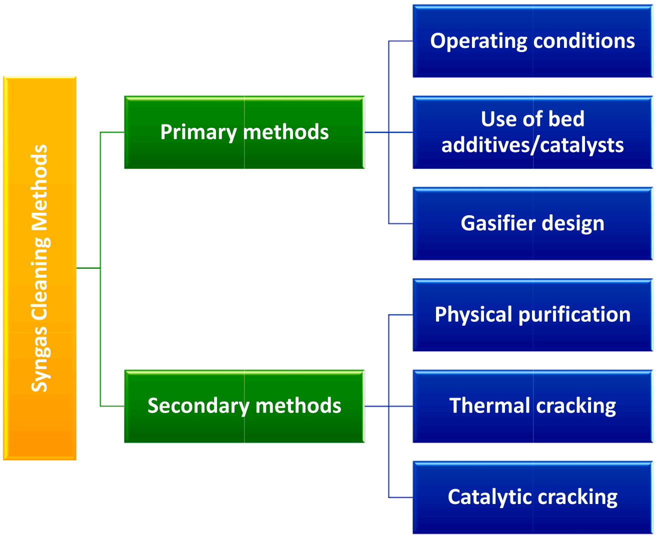

Fig. 9. The primary and secondary strategies for syngas cleaning during the gasification process.

tends to improve over gasification time periods, attributed to the initiation of calcium oxide layers [128]. Guo et al. [129] developed a Fe-RHC catalyst through impregnation and one-step pyrolysis for tar eradication. Schmid et al. [130] found that using limestone or dolomite in gasification depresses tar production from 27 to 7 g/Nm^3, boosts H_2 and CO levels and reduces CO_2 and CH_4. It also cuts H_2S and COS levels by up to 40% and 60%, respectively. Lu et al. [131] describe adding Fe to CaO further drops HCN and NH_3 significantly.

6.1.3. Effect of gasifier design

Gasifier redesign or the creation of novel gasifier designs, become imperative to secure a purified product gas. Biomass gasifiers yield different tar levels: updraft (highest, around 100 g/Nm^3, primary and some secondary tar), downdraft (lowest, around 1 g/Nm^3, tertiary tar) and fluidized-bed (intermediate, around 10 g/Nm^3, mix of secondary and tertiary tar) [132] as shown in Fig. 12**(a)**. Tar, moving with product gas, has concentrations around 5–20 g/Nm^3 for bubbling and 1–5 g/Nm^3 for circulating fluidized beds. In entrained flow gasifiers, minimal tar is released and subjected to high (> 10,000 °C) temperatures, resulting in significant tar reduction via thermal cracking [20]. Fig. 12**(b)** illustrates the impact of wood, waste (RDF/MSW) and agro-residue on tar content when air is utilized as the gasifying media. It is evident that the median tar content is notably elevated for waste in comparison to wood or agro-residue across gasifier types, particularly in fluidized bed configurations as opposed to downdraft gasification of waste [15]. Fluidized bed gasifiers (bubbling or circulating) enhance biomass conversion through vigorous mixing of biomass and bed material. This hydrodynamic environment facilitates significant biomass-to-fuel-gas conversion, partially oxidizes biomass carbon, and reduces tar formation. Typically, pyrolysis and gasification are combined in a two- or three-stage process, either in a single unit or in sequential reactors. Both setups achieve high efficiency by maximizing char conversion and producing clean syngas with minimal tar. However, using separate reactors adds complexity to the process [133].

6.2. Secondary techniques

This approach uses distinct gasifiers to eradicate impurities content in the syngas to meet the required standards. Secondary methods include physical purification, thermal cracking at increased temperatures and catalytic cracking [72]. Physical methods include cyclones, various filters (baffle, fabric, or ceramic), rotating particle separators, electrostatic precipitators and scrubbers (using water or organic liquids) [69]. Tars, halides, sulfur and alkaline components are parted using scrubbers, spray towers and electrostatic separators. However, these methods struggle with certain hydrocarbons, especially hydrophobic ones, due to their low water solubility and the challenge of managing significant volumes of contaminated water [5]. Physical systems are most effective at lower operating temperatures but may produce residual waste. Secondary treatments in a separate reactor focus on comprehensive tar conversion, achieving nearly 100% tar removal with catalytic methods. Physical-mechanical methods offer 99% efficiency in tar removal but trade-off with reduced energy conversion and hazardous waste. Thermal cracking is efficient (up to 98%) in tar removal.

6.2.1. Effect of physical mechanisms

Physical impurities extraction enhances gasification's commercial viability due to lower operational and maintenance costs compared to catalytic approaches. These methods are into dry and wet cleaning methods [20]. Dry gas cleaning operates at 200–800 °C, sometimes requiring gas cooling for fabric filter use [98]. Wet gas cleaning processes are executed after this cooling stage, operating within a temperature spectrum of 20 to 60 °C. Table 7 outlines impurities in biomass

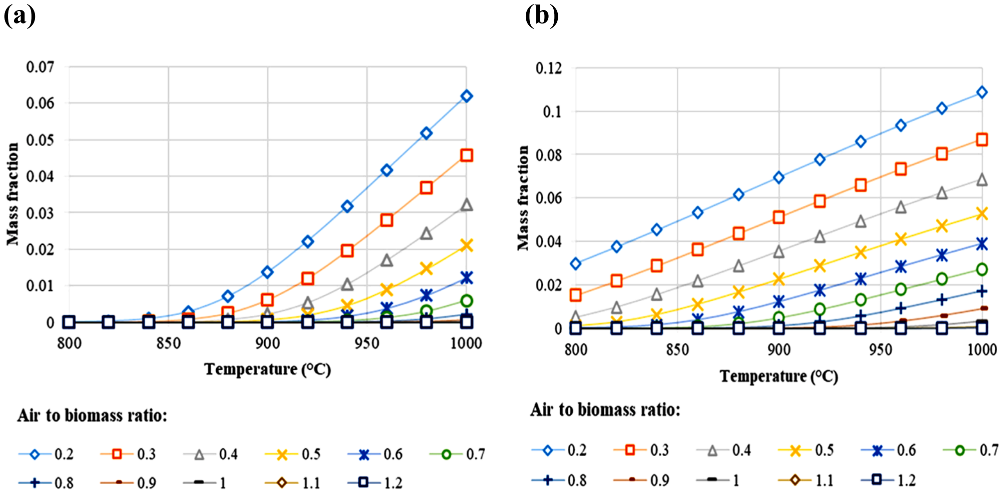

Fig. 10. The impact of gasification temperature and air-to-biomass ratio on the proportion of total tar generated in the gasification region is examined for particle sizes ranging from 0.2 to 0.5 mm, considering two different pyrolysis temperatures: (a) Tp = 600 °C and (b) Tp = 500 °C. Reproduced with permission from [92], Copyright ACS ©2022.

Table 5
The characterization of a variety of gasifying agents and their properties.

Gasification agent	Air	Oxygen	Steam	Carbon dioxide
Properties	Employing partial combustion to generate heat for gasification Moderate presence of char and tar.	Reduce tar levels, enhance H_2, CO and CH_4 in producer gas Improve carbon conversion properties	Producer gas with a high heating value Producer gas enriched with H_2 (e.g., 450% by volume)	Producer gas with a high heating value Producer gas with high H_2 and CO levels and low CO_2 levels.
Product gas LHV, MJ/Nm^3	Low: 4–6	High: 10–15	High: 15–20	–
Products	CO, H_2, water, CO_2, HC, tar, N_2	CO, H_2, HC, CO_2	H_2, CO, CO_2, CH_4, light HC, tar	–
Composition of gas formed (vol./vol. or mol./mol.)	H_2—15% CO—20% CH_4—2% CO_2—15% N_2—48% H_2:CO: 0.75	H_2—40% CO—40% CO_2—20% H_2:CO: 1	H_2—40% CO—25% CH_4—8% CO_2—25% N_2—2% H_2:CO: 1	–
Gasification temperature	900–1100 °C	1000–1400 °C	700–1200 °C	–
Cost	Cheap	Costly	Medium	
Advantages	Inexpensive fuel source, highly efficient, plentiful resources, moderate tar production	Moderate energy value gas, limited gas volume, minimized sensible heat loss, enhanced efficiency, minimal tar content, high concentration of combustible components	Efficient hydrogen production, generation of both high and medium energy value gas and excellent gas quality enable direct fuel usage.	–
Disadvantages	Due to its high nitrogen content and low hydrogen volume fraction, the product gas has a low energy value and is typically used as a raw material for chemical synthesis gas.	High energy usage for oxygen production, elevated costs and inefficient economy.	Additional equipment is necessary, leading to increased system complexity and cost while decreasing equipment autonomy.	–
Reference	[88,96]	[88,96]	[88,96]	[6]

gasification and associated issues, along with their physical removal methods. Impurities include particulates, alkali metals, nitrogen, sulfur, chlorine and tar. Various physical techniques such as cyclones, scrubbers, filtration, electrostatic separation and adsorption are employed, achieving up to 100% removal efficiency. Cyclonic separators can remove 30–70% of tar at temperatures between 100–900 °C. Filters are crucial for both wet and dry cleaning: fabric filters remove 0–50% of tar at 130–600 °C, sand filters remove 50–97. % at 10–20 °C, and ceramic and glass filters remove 74–97% at 650–700 °C. Catalytic filters, using different catalysts or structures, can achieve tar elimination efficiencies of over 95%, sometimes reaching 97–99% [5].

Although hot gas purification helps preserve the calorific value of syngas, wet/dry gas cooling and scrubbing have become the method of choice due to their superior efficacy in diminishing the tar dew point. Typically, chilled water is utilized for gas cooling, concurrently extracting particulate contaminants and tar constituents from the gas flow. Alternatively, organic scrubbing liquids are utilized in a technique known as OLGA (Organic Liquid Gas Absorption), offering an alternative to water-based scrubbing. Fig. 13**(a)** depicts a performance evaluation of OLGA with traditional techniques like wet scrubbers and wet ESP (Electrostatic Precipitators). OLGA exhibits engaging results, gaining elimination efficiencies exceeding 99% for all tar classes. In contrast, ESP and wet scrubbers demonstrate selective tar elimination efficiency contingent on tar classes, typically gaining efficiencies in the fluctuating of 50–75% [15]. Paethanom et al. [134] employed an absorption-adsorption approach utilizing vegetable and waste cooking oil scrubbers as absorbers, along with rice husk and rice husk char beds as adsorbents. This method demonstrated a 95.4% efficacy in eradicating gravimetric tars during rice husk pyrolysis. The absorption procedure exhibited effectiveness in eliminating heavy tars, while the adsorption method was found to be efficient in removing light tars.

Irfan Ul Hai et al. [135] demonstrated that employing three strategies for tar reduction yielded comprehensive results. Notably, the innovative approach utilizing a mop fan integrated with water spray exhibited the greatest efficacy, lowering tar concentrations to 0.987 mg/L. In contrast, the utilization of woodchips and the mop fan absent of water spray yielded tar levels of 0.459 mg/L and 0.617 mg/L, respectively as shown in Fig. 13**(b)**. The effectiveness of the mop fan with water spray is attributed to the presence of suspended water droplets, which enhance tar removal efficiency significantly. Thus, implementing a mop fan with a water spray as a cleaning unit in gasifiers offers a practical solution for removing hazardous waste and contaminants [135]. In conclusion, filtration cleaning techniques have achieved a TRL of 8–9. Additionally, the OLGA procedure, which has been commercialized, has reached a TRL of 9 [5].

Membrane technology is extensively employed for separation processes and selective catalytic reactions across water purification, environmental preservation and energy-related applications. This technique predominantly relies on the preferential transport of compounds through membranes by means of size-based exclusion or solution-diffusion mechanisms [136]. Additionally, membranes are often combined with other separation techniques like absorption and distillation to enhance efficiency, save energy and reduce waste [137] as shown in Fig. 14. Ceramic membranes are renowned for their exceptional thermal and chemical durability, making them suitable for diverse processes across various temperatures, pressures, and pH levels. A recent innovation in this field is the phase-inversion assisted extrusion process, used to create micro-tubular ceramic membranes with a sophisticated bimodal pore structure. Membrane contactors offer up to 30-fold greater surface area than gas absorbers and 500-fold more than liquid–liquid extraction columns, enabling highly efficient separation. Achieving the low tar and contaminant levels required for methanol synthesis, though slightly more expensive, can be optimized by integrating catalytic membranes with membrane scrubbers, ensuring superior syngas conditioning due to their high separation efficiency [136].

6.2.2. *Effect of thermal cracking*

Tar undergoes thermal cracking at high temperatures, converting it into lighter gases by altering its stability and composition [138] as shown in Fig. 15**(a)**. Elevated temperatures decrease tar yield and increase gaseous product production [139]. The feasibility of thermal tar cracking is contested, largely due to the requirement for elevated temperatures, typically above 1100 °C, to achieve effective purification. Some researchers have explored alternative methods such as plasma thermal cracking and microwave thermal cracking [140], both of which have shown promising results in achieving high cracking efficiencies. Plasma is categorized as equilibrium or nonequilibrium based on particle temperatures and energy levels. Thermal methods are widely employed for activation, cracking and pyrolysis due to their high

Table 6
A comprehensive overview of previous studies related to biomass gasification.

Gasifier type	Biomass feedstock	Gasifying agent	Temperature (°C)	ER/SB	Gas composition (%)				Syngas HHV/LHV (MJ/Nm^3)	Efficiency/ energy recovery (%)	Gas yield	Tar content	Reference
					H_2	CO	CO_2	CH_4					
Top lift updraft	Palm kernel shell, bituminous coal	Air	600–800	0.26–0.34	–	20	–	4.0	LHV: 3.70	CGE: 34 to 46 CCE: 66 to 83	1.98 to 3.26 m^3/kg	–	[106]
Fixed bed downdraft	Wood chips	Air	847	0.335	15.1-16.4	23.8-20.6	9.39-11.3	2.28-1.83	LHV: 5.86–5.18	CGE: 76.9-71.9	2.32–1.84 Nm^3/kg	–	[107]
Autothermal downdraft	Garden waste, LDPE	Air	700–900	0.29–0.31	10.7-13.53	14.8-19.5	11.5-18.1	1.35-2.24	LHV: 3.5–4.7	CGE:43.8-61.8	40.5 Nm^3/h	8.1—5.7 g/Nm^3	[108]
Open top-draft	Eucalyptus wood	Air	800–1000	0 3–0.4	10.8	13.3	9.0	0.9	3.709	–	24.47–24.98 kg/kmol	–	[109]
Downdraft fixed bed	Garden waste and coal	CO_2	450–650	0.23–0.2	7.2-9.6	6.8-11.7	11.2-14.8	1.3-1.7	20.7–2.74	CEG: 57.5	86.3 MJ	66.1 MJ	[110]
Fixed bed	Waste wood	Steam	1000	SB:5.7	48.8–67.2	4.5–8.8	39.0–21.8	7.7–2.2	HHV:16.5–17.5 MJ/kg	–	77.8-95.8 %	21.2–42.9 g/Nm^3	[111]
Fixed bed	Wood	Air, CO_2	700–800	0.24	18.0	26.7	14.1	3.4	–	CGE: 60	67 m^3/h	–	[112]
Fixed bed	Seage sludge, acid hydrolysis residue	Air	600–800	0.15–0.3	11.6	16.7	17.6	5.94	LHV: 6.83	CGE:70.68	1.20 Nm^3/kg	5.84 g/Nm^3	[113]
Quartz fluidized bed	Rice husk	Air	700–900	–	11.89	12.38	17.11	4.58	–	–	73.2 %	15.6 %	[114]
Circulating fluidized bed	Rice husk, sawdust, bamboo dust	Air	750–900	0.19–0.35	8.79	15.34	18.93	11.07	HHV: 4.71–5.39	CCE: 58.7-80.23	1.73–1.75 Nm^3/kg	–	[115]
Fluidized bed	Beech wood, sawdust, waste wood	Air, steam	700–805	ER:0.24–0.37	0.2	0.16	0.36	0.13	HHV: 6.9	PER: 59	–	–	[116]
Fluidized bed	Pine sawdust/ coal	Steam	700–1000	ER: 0.1–0.4	–	–	–	–	HHV: 13.8	PER: 92.3 CCE: 84.2	–	–	[117]
Fluidized bed	Beechwood, polyethylene	Steam	850	Wood-to-PE ratio: 1:1,3:1 and 4:0	37.1	23.6	–	–	LHV: 8.7	CCE: 92.1	–	–	[118]
Fluidized bed	MSW, pine dust	Air	700–900	0.5–0.2	9–11	17–19	15–19	4–6	LHV: 5.3	–	1.34–1.15 Nm^3/kg	5.4—10.1 g/Nm3	[119]
Fluidized bed	Sewage sludge, coal	Air, steam	800	0.29–0.31	7–27	9–11	12–15	1–4	LHV: 2–6	CGE: 80.56 CCE: 67–75	–	0–210 mg/Nm^3	[120]
Fluidized bed	MSW, switchgrass	Air	700–900	0.2	10	14.1	15–18	2.4	LHV: 6.2–6.7		1.4–1.6 Nm^3/kg	9.9 g/Nm^3	[121]
Fluidized bed	Peach stone, miscanthus	Air	750–850	–	11.03	13.2	4.3	15.8	–	–	–	–	[122]
Bubbling fluidized bed	Wood chips	Air	750–900	0.1–1.1	5-6	1–23	6-14	1-6	–	–	–	–	[123]
Moving grate	Biomass waste	Air	200–800	0.28	12.50	22	9.94	3.99	LHV:5570 kJ/m^3	CGE:67.50	2.01 m^3/kg	–	[124]
Batch tank	Soyabean	Air	600–700	–	18	15	30	37	–	CGE: 37.5-74.28	–	–	[125]

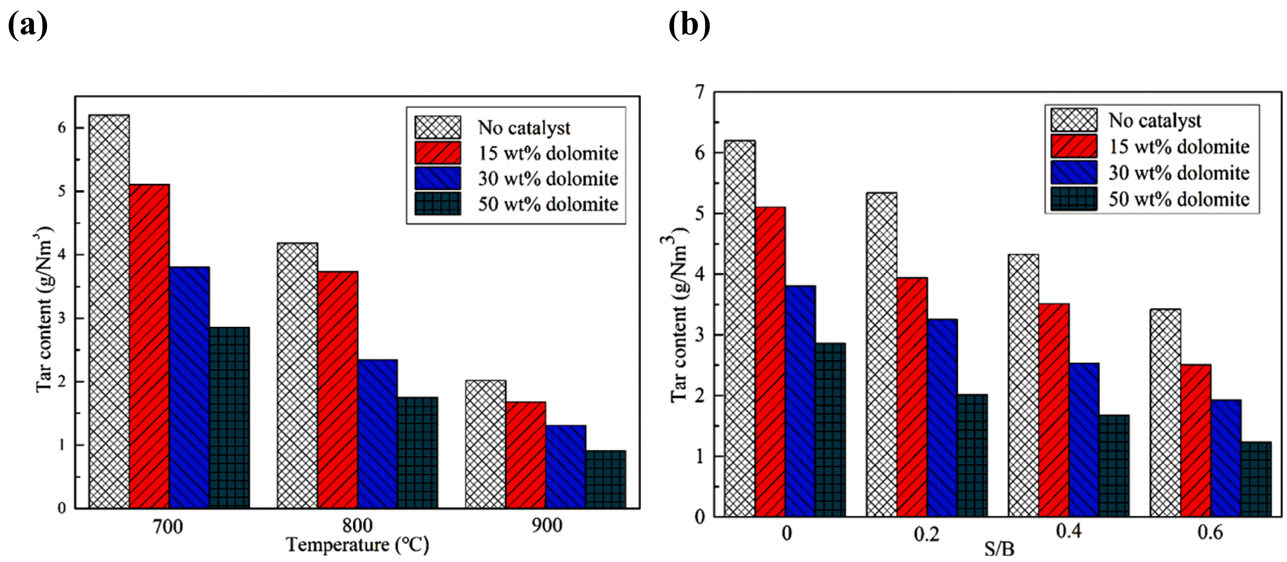

Fig. 11. The formation of tar in relation to changing bed conditions; (a) Temperature variations and (b) S/B ratio at 700 °C. Reproduced with permission from [126], Copyright ACS ©2020.

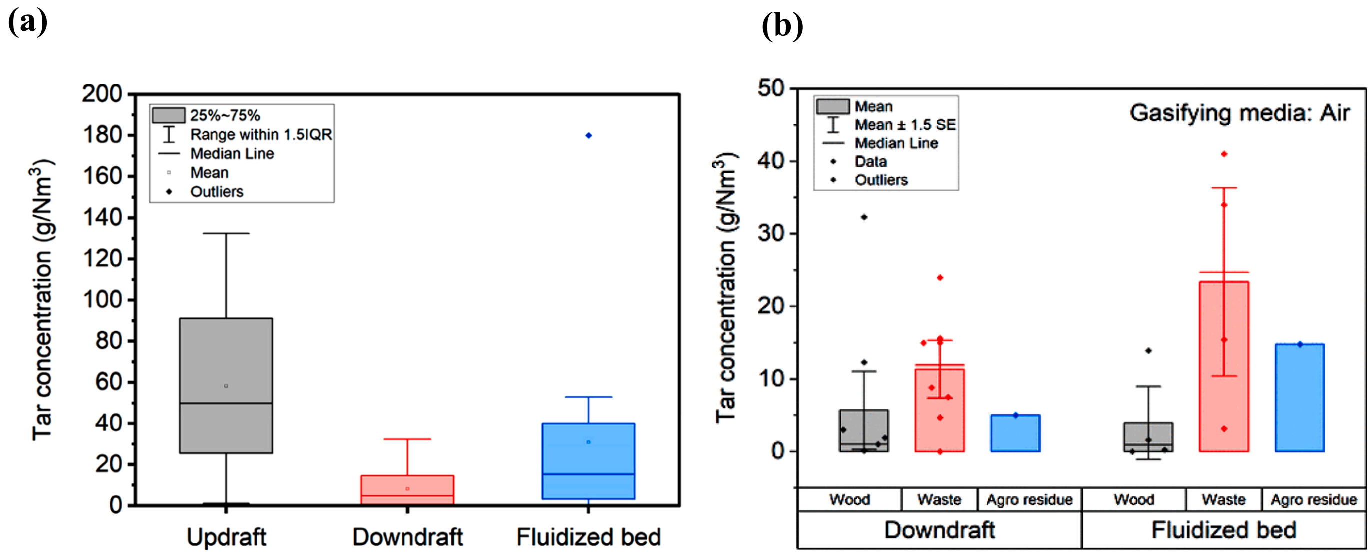

Fig. 12. (a) A box plot illustrating the concentrations of tar across different types of gasifiers and (b) the impact of wood, waste (RDF/MSW) and agro-residue on tar concentration when air is utilized as the gasifying medium. Reproduced with permission from [15], Copyright ACS ©2024.

temperatures, energy density, large capacity and efficiency. Nonthermal plasma (NTP) technology presents key benefits for efficient H_2 production [141]. Tar derived from rice husk pyrolysis underwent thermal cracking method spanning temperatures between 900 to 1200 °C, alongside a residence time of 5 s. This process ended in a continuous reduction in tar compounds from 105 g/kg dry rice husk to 0.018 g/kg dry rice husk, achieving an impressive tar cracking rate of 99.9% [142]. Microwave thermal cracking of toluene, serving as a model tar, achieved a cracking rate of 95.12% at 800 °C when coupled with a biochar-Ni catalyst at 4 wt% loadings [140].

Furthermore, tar generated from the co-gasification of coconut shell and charcoal underwent thermal treatment using a programmable muffle furnace, covering temperatures ranging from 700 to 1000 °C. It was observed that the efficiency of tar eradication escalates from 81.87 to 97.25% with escalating temperatures [143]. Plasma is greatly efficient for eliminating gaseous pollutants and resolving tar issues in producer gas, with flexibility for catalyst integration to enhance tar conversion into valuable products like H_2 and CO. Carbon conversion can reach 100%, greatly increasing syngas value, though its high electricity consumption, accounting for 15–20% of plant output, remains a limitation [144]. Mei et al. [145] performed Aa hybrid plasma-catalytic system for steam reforming tar compounds using honeycomb-based catalysts in a gliding arc discharge (GAD) reactor as shown in Fig. 15 **(b-f)**. The introduction of honeycomb materials in GAD increased reactant molecule collisions with plasma reactive species, enhancing conversions. Ni/γ-Al_2O_3 exhibited the best performance, achieving high toluene (86.3%) and naphthalene (75.5%) conversions, with H_2 (35.0%) and CO (49.1%) yields while inhibiting byproducts. The highest energy efficiency was 50.9 g/kWh, 35.4% higher than plasma alone. The coated honeycomb material demonstrated strong carbon resistance and stability.

6.2.3. *Effect of catalytic cracking*

Effective catalysts in biomass gasification must lower pyrolysis activation energy, reduce gasification agent needs, and enable targeted catalytic tar conversion. The catalyst typically comprises a catalytic

Table 7
The Impurities present in biomass gasification process, issues related to their presence and physical cleaning methods for their removal.

Contaminants	Common compounds	Presence	Problems	Removal technique	Removal (%)	Reference
Particulates	Heavy metals, Traces of Hg, Cd	Ash, char, condensable and bed material.	Wear on metals and pollution, disposal costs.	Cyclones Filtration Electro-static separations Wet scrubbing	90 ~99 – ~95	[85]
Alkali metals	Salt forming compounds	Vapor phase.	Metal corrosion and altered ash melting points.	Condensation Adsorption Wet scrubbing	– 98 –	[21]
Nitrogen	NH_3 and HCN	NOx emissions during combustion.	NOx pollution effecting downstream catalysts.	Thermal catalytic decomposition Wet scrubbing	80 Vary	[85]
Sulphur	H_2S and COS with some thiophenes and mercaptans.	Usually not problematic.	Harmful pollutants corrode metals and poison downstream catalysts.	Adsorption Chemical solvent methods Liquid redox process	99 – 100	[85]
Chlorine	Predominantly HCl with minor amounts of CH_3Cl.	Usually not an issue.	Emissions, corrosion, ash fusion, sintering and K interactions.	Adsorption Wet scrubbing	80 –	[21]
Tar	Aromatic and polyaromatic hydrocarbons	Bituminous oil in producer gas is complex to remove due to its composition	Condensation challenges, equipment issues, gas conditioning, catalyst deactivation.	Thermal cracking Non-thermal plasma Catalytic cracking	80 Vary Vary	[85]

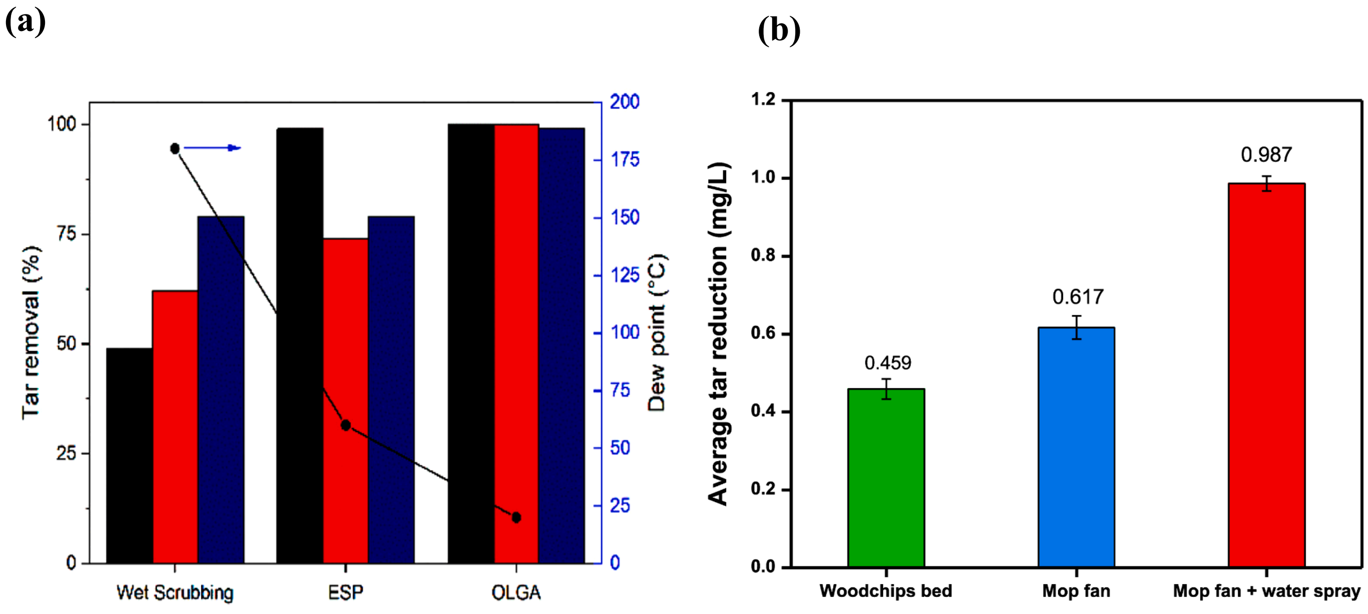

Fig. 13. A comparison of various tar capture methods; (a) Tar ermoval percentage with dewpoint and (b) Tar reduction with single and combined methods. Reproduced with permission from [15] Copyright ACS ©2024 and [135], Copyright Elsevier ©2019.

metal, a stability-enhancing promoter, and a supportive structure. This helps to convert the tar compounds into light hydrocarbons [73]. Guan et al., [79] proposed a classification of six catalyst groups; (1) nickel-based, (2) transition metal-containing, (3) alkali metal-incorporated, (4) natural source-derived, (5) zeolite-based and (6) activated carbon-centre or chars. Table 8 shows the pros and cons of a variety of catalysts utilized for tar removal. In biomass gasification studies, nickel-based catalysts, dolomite and olivine are prominent, especially in fluidized bed reactors. Frequently utilized supports for tar cracking include activated carbon, biochar and mineral char, owing to their porous architectures. The catalytic performance is contingent upon parameters such as surface area and pore size, which facilitate metal ion dispersion and the transport of reactant molecules within the catalyst [79].

Within the domain of transition metals, notably within Group VIII, nickel finds extensive utilization in industrial environments, particularly for steam and dry reforming reactions. Nickel catalysts exhibit pronounced efficacy in steam reforming of heavier hydrocarbons in comparison to lighter ones. They significantly contribute to water gas shift reactions and effectively convert tar compounds [153]. They contribute to reducing tar content and improving the H_2 to CO ratio, enhancing synthesized gas quality [154]. Miyazawa et al. [155] established a hierarchy of activities among natural catalysts, with $Ni/Al_2O_3 > Ni/ZrO_2 > Ni/TiO_2 > Ni/CeO_2 > Ni/MgO$. Nonetheless, quick deactivation resulting from carbon buildup on the catalyst surface and susceptibility to fouling by coke, sulphides, metal chlorides and alkali oxides present substantial obstacles [79]. These catalysts demonstrate effectiveness in eliminating both tar and ammonia during coal or biomass gasification processes. However, catalyst deactivation, especially coking in nickel catalysts, is a key challenge. To combat this, a combination of nickel with alkali or alkaline earth metals, like using calcined dolomite or adding magnesium, which reduces coke formation [65]. Tar breakdown can be done in a secondary reactor or by mixing the catalyst with the fuel, through complicated catalyst recovery [63].

Customized metal catalysts such as Rh, Ru, Pd and Pt effectively

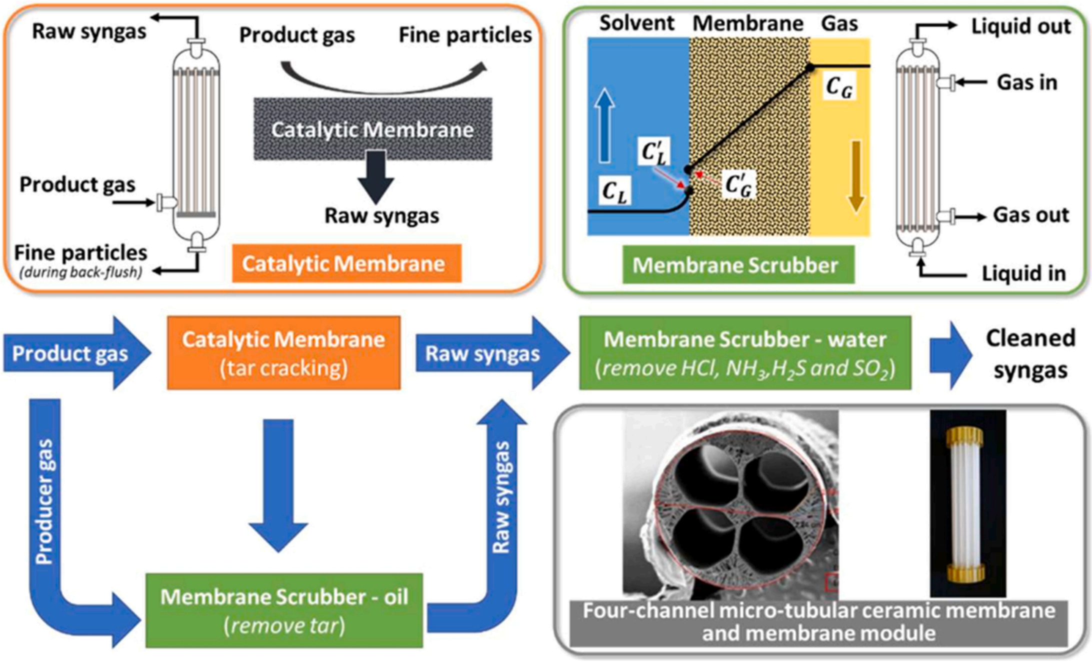

Fig. 14. Illustration of various membrane-based configurations for producing purified syngas. Reprinted with permission from [136], Copyright Elsevier ©2024.

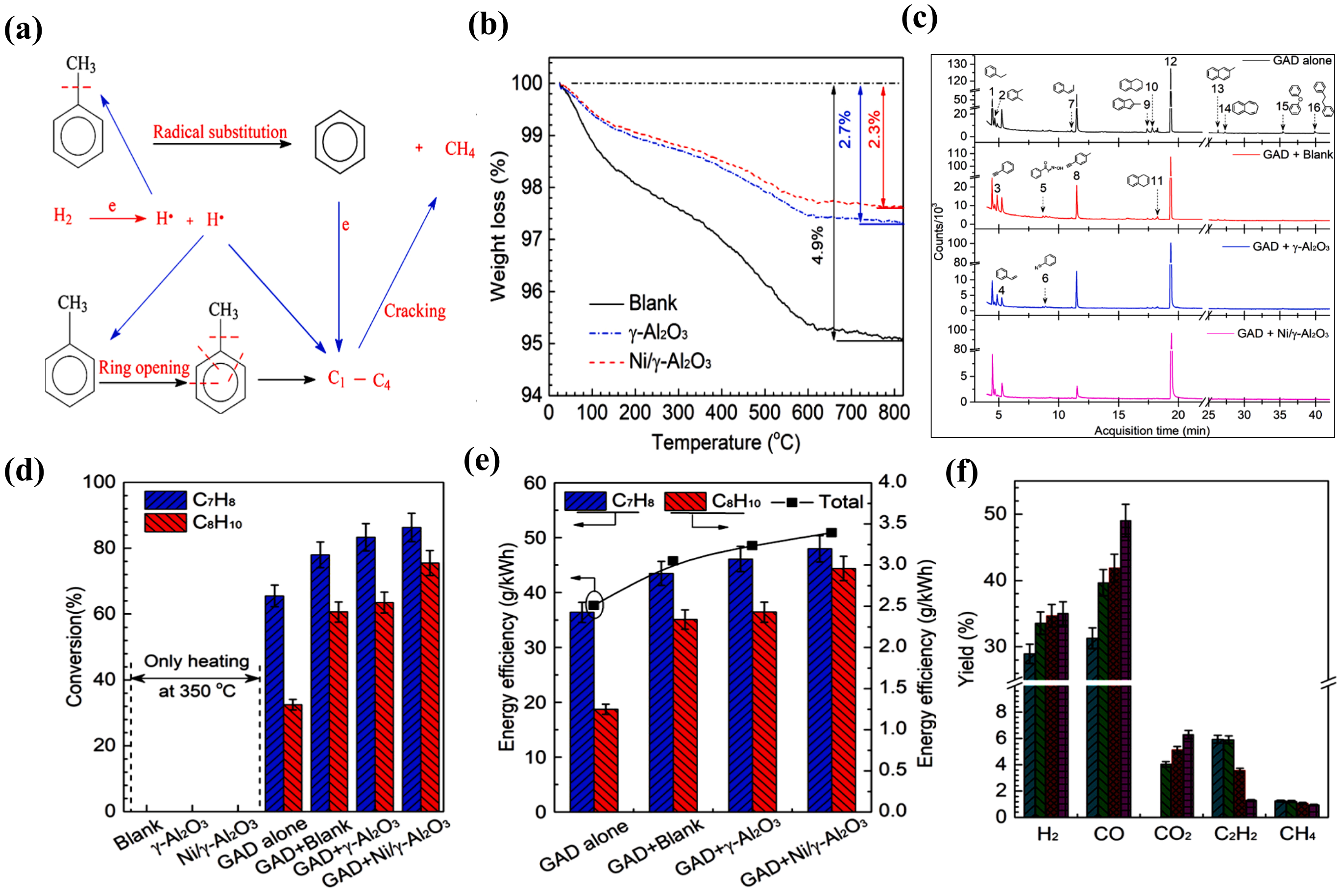

Fig. 15. (a) The mechanism of toluene cracking at high temperatures. Reprinted with permission from [138], Copyright ACS Publications 2018. (b) TGA curves at 600 °C (c) GC–MS analysis (d and e) difference in tar conversion and energy efficiency and (f) yield of syngas during plasma gasification. Reprinted with permission from [145], Copyright ACS ©2022.

Table 8
Merits and demerits of various catalysts utilized for the elimination of tar.

Catalyst types	Sub-types	Merit	Demerit	References
Natural catalysts	Limestone	Cost-effective catalyst with exceptional performance also safeguards valuable catalysts.	Experiences significant pulverization and wear.	[146]
	Olivine	Easily accessible and cost-effective, with high wear resistance.	Reduced catalytic efficiency.	[86]
	Iron ore/ limonite	Abundant. Inexpensive.	Less effective than olivine, deactivates in reducing atmospheres.	[147]
Alkali metal-based		Made via gasification, no reprocessing needed post-deactivation.	Sinters at high temps, less effective than olivine.	[148]
Ni-based catalyst		Cost-effective, abundant, 8-10x more active than dolomite.	Rapid deactivation from coke formation – at low temperature. Require a support or secondary catalyst for better efficiency.	[63,65,149]
Char		Abundant, cost-effective, no regeneration needed, superior to olive, stays neutral/alkaline.	Balances gasification and tar catalysis. Unstable, feedstock-dependent behaviour.	[150]
Transition metal-based		Operates hot, boosts H_2 and CO, and excels at tar removal. Made via gasification.	Costly, quickly inactivated by poisoning, hard to regenerate.	[151]
Zeolite		Significant catalytic effectiveness.	Complex synthesis, resulting in higher cost.	[152]
Activated aluminium oxide		Superior activity compared to live.	Quick deactivation upon exposure to soot.	[146]
Fluid catalytic cracking (FCC)		Cost-effective, versatile applications, continuous gasifier generation, no regeneration needed.	Deactivates with soot, weaker catalytic power than olive.	[146]

decrease tar formation in biomass gasification, particularly during steam reforming conditions [156]. These catalysts resist sulphides and sustain thermal stability, particularly Rh-based ones which exhibit superior tar eradication capabilities, with performance order in gasification scenarios as follows: Rh > Pt > Pd > Ni = Ru [20]. However, their higher expenditure compared to nickel catalysts poses a challenge for widespread adoption. Alkali metal catalysts are also securing in enhancing product gas quality through tar steam reforming [154]. Natural minerals like dolomite ([$CaMg(CO_3)_2$]) and olivine ([$(MgFe)_2SiO_4$]) offer potential use as catalysts after specific pretreatment steps, like calcination. These minerals are cost-effective, abundant and demonstrate significant efficacy in tar reforming processes [23]. A novel nano-catalyst was synthesized using a modified sol–gel method with activated biochar, Ni as the active component and Co as the promoter for tar conversion into H_2. The 6% Ni – 4% Co/char catalyst achieved a high H_2 yield of 263.84 g H_2/kg TMCs and nearly 100% TMC transformation, outperforming traditional catalysts by over 30%. It also showed excellent resistance to carbon deposition, oxidation, and sintering due to the formation of a stable Ni – Co alloy, high oxygen affinity of Co and enhanced Ni dispersion on a high specific surface area (920.61 m^3/g) as shown in

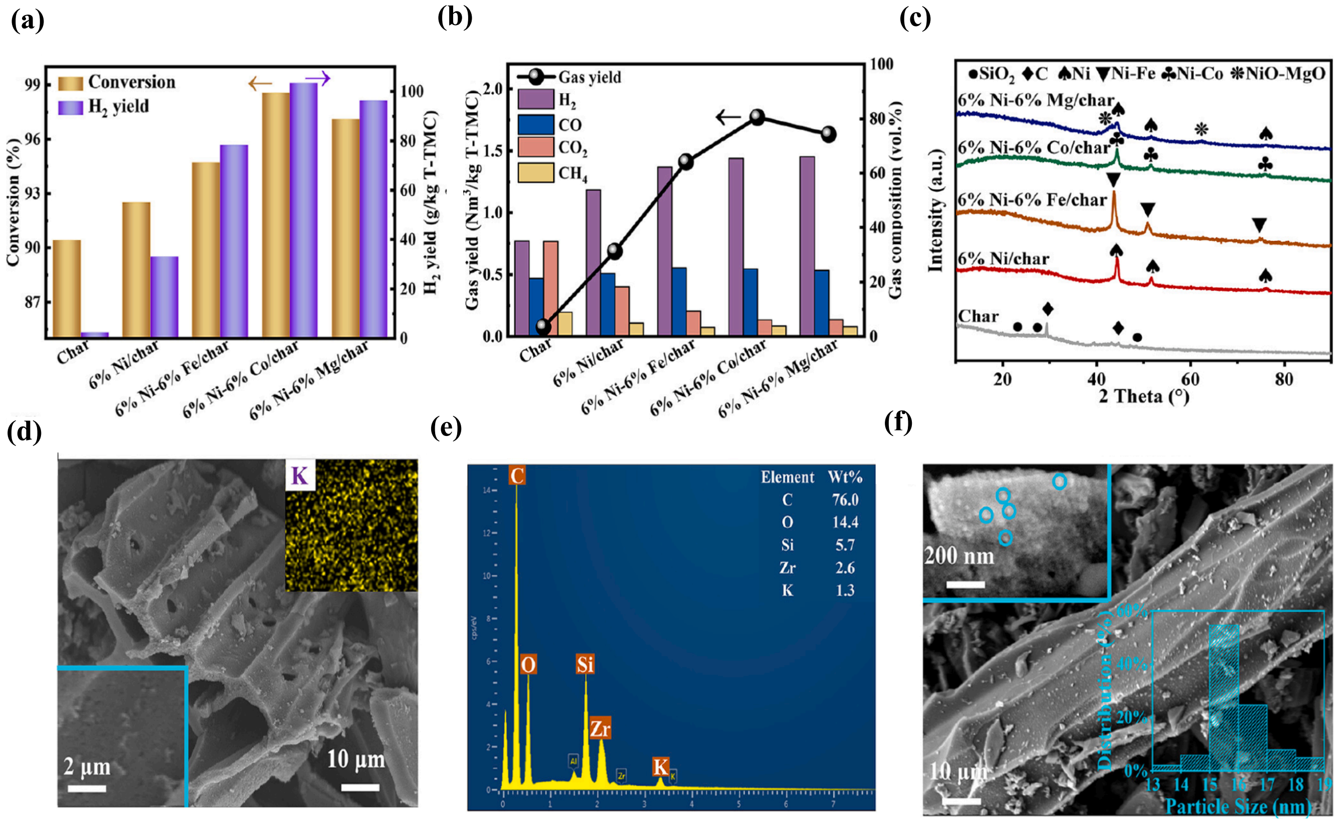

Fig. 16. Influence of different catalysts on; (a) T-TMC transformation and hydrogen yield, (b) Product gas yield and composition at 700 °C, (c) Catalysts XRD pattern, (d) SEM image of char, (e) EDS analysis pf char and (f) SEM image of Ni/Char catalysts. Reprinted with permission from [157], Copyright ACS ©2024.

Fig. 16 [157].

Biochar, derived from biomaterial gasification, is an economical and readily accessible carbon-based metal catalyst that has garnered substantial interest for catalytic tar cracking. Enhancement of biochar properties is achieved through physical or chemical activation processes. Chemical activation, e.g., with KOH or K_2CO_3, enhances porous characteristics and catalytic performance at lower temperatures compared to physical activation (using H_2O, CO_2 or both) [158]. One study showed 91.75% tar decomposition using KOH-activated carbon at 800 °C (catalyst-to-feedstock ratio 2:1) [159]. Another study uncovered a 90.4% tar conversion increase through CO_2 etching of iron-supported sawdust biomass, boosting Fe^0 content and enhancing porous properties [160]. In a separate study on catalytic syngas purification, activated carbon (AC) outperformed biochar due to its superior porosity and higher ash content, as compared to biochar [161]. Buentello-Montoya et al. [162] demonstrated that employing charcoal or activated charcoal catalysts boosts the calorific value of the gas while concurrently diminishing its tar content. Table 9 provides a detailed overview of different studies conducted by using a variety of catalysts in biomass gasification.

7. Scalability aspects of biomass gasification technology

Research on biomass gasification has been ongoing since the late 20th century to produce fuels and chemicals [186]. In this process, biomass is heated at high temperatures with controlled amounts of oxidizing agents like steam, air, or oxygen to generate syngas [187], a mixture of gases including H_2, CO, CO_2, CH_4 and N_2 [188]. The composition of the syngas depends on factors such as the type of gasifying agents, the gasifier used and various operating conditions including temperature, equivalence ratio, feedstock type, moisture content, particle size and catalysts [189]. Regarding gasifying agents, steam is ideal for both small and large-scale systems, producing syngas with high H_2 content (over 60 vol%) and lower CO_2 and methane. Air is more suitable for small-scale and lab-scale gasifiers, yielding gas with 5–40 vol% H_2, along with N_2 and CO [188]. Catalysts play a crucial role in influencing the gas composition and facilitating CO_2 capture [190].

Gasification utilizes three main types of gasifiers and agents, each with specific advantages and drawbacks. Fixed bed gasifiers have lower gas flow velocities and simpler designs, making them cost-effective for small-scale operations and producing cleaner gas with lower tar levels. Fluidized bed gasifiers, on the other hand, feature higher gas flow rates, uniform temperature distribution and enhanced mixing, making them efficient and versatile for various biomass feedstocks and both large and small-scale operations. Fluidized bed reactors are preferred for their high efficiency and better heat transfer, while fixed bed reactors are valued for their straightforward, economical approach. Entrained flow gasifiers, though highly efficient for coal in large-scale settings, are less suitable for biomass [186]. Small-scale CLG units offer greater flexibility and ease of installation compared to larger units, making them ideal for distributed biomass utilization applications [63]. The choice between the two depends on specific needs, feedstock types and desired outcomes [188].

Another criterion for assessing the scalability of a technology is the Technology Readiness Level (TRL). TRL is a point-based system used to assess the maturity of a technology from initial concept to commercial use [191]. Developed by NASA in the 1970 s, the TRL scale ranges from 1 to 9, with higher numbers indicating greater maturity. It is divided into three stages: concept to lab scale (TRL 1–4), lab to pilot scale (TRL 4–6) and pilot scale to commercialization (TRL 6–9) [192]. The TRL framework helps guide research, investment and commercialization efforts by evaluating the progress and readiness of technologies [191]. Gasification technology has attained a TRL of 8–9. Similarly, syngas cleaning techniques for internal combustion engines and turbines have extended a TRL of 8–9, whereas for fuel cells, it is still at a TRL of 1–4 [5]. In power generation, syngas-based combustion engines and biomass gasification systems, known as BIGCC, generally have a TRL of 4–6 [5]. Combined Heat and Power (CHP) systems, which produce both electricity and heat, are commercially established with many operational plants worldwide, including small-scale units in China, Japan and Europe, and large-scale plants in Denmark. The TRL for CHP systems ranges from 4 to 7 [193]. For instance, the Valmet plant in Lahti, Finland, operational since 2012, uses wood chips to generate 50 MW of power and 90 MW of district heating, reflecting a TRL of 6–7 for turbines, with 1–4 for gas turbines and 6–7 for steam turbines in biomass gasification systems [5].

8. Techno-economic assessment

Gasification is recognized as an efficient method for deriving energy, chemicals, and hydrogen from biomass [18]. The economic and energetic performance of energy production facilities depends on numerous factors, including the condition and transportation of the biomass, as well as plant operating costs [194]. The maturity of technologies and

Table 9
A detailed overview of different studies conducted by using a variety of catalysts in biomass gasification.

Catalysts	Gasifier type	Feedstock/ model compound	Temperature (°C)	H_2 yield	Tar cracking (%)	References
$NiFe_2O_4$ OC	Fixed bed	Toluene	850	81.25 g/kg	96.83	[163]
Fe-Ni/CNF	Two-stage fixed bed	Wood chips	700	53.58 g/kg	85.76	[164]
Ni-Cu/ASC	Two-stage fixed bed	Aspen wood sawdust	800	54.34 g/kg	93.20	[165]
SC@0.1Ni-Fe	Two-stage fixed bed	Sargassum, peanut shell	600	25.34 g/kg	90.07	[166]
Ni/ZSM-5	DBD plasma reactor	Toluene	300	39.07 g/kg	97.30	[167]
BC-FeNi	Fixed bed	Toluene	800	78.38 g/kg	80	[168]
6 %Ni-4 %Co/char	Two-stage quartz fixed bed	Pine sawdust	700	111.46 g/kg	99.59	[157]
$Ru/SrCO_3-Al_2O_3$	Fixed bed	Toluene	600	–	11.8 -80	[169]
Ca	Dual stage reactor	Waste peat	900	60.5-68.5%	94.4	[170]
Ru and Ni	Fixed bed quartz reactor	Toluene	400–800	–	97.8	[171]
$Ni-xSiO_2$ @C	Tubular fixed bed quartz reactor	Basswood	500–650	135 μmol/min	97	[172]
Ni-doped	–	Corncobs	600	–	60	[173]
Ni-Pt	Quartz tube reactor	Toluene	300–600	–	90.4	[174]
Fe-Ni	Fixed bed U type S	Toluene	500–700	>2000 mmol/(g-cata)	63.8–100	[174,175]
Ni, Fe and Mg	Fixed bed	Toluene	800	–	86	[176]
$CaO-Ca_{12}l_{14}O_{33}$	Fixed bed	Toluene	600–800	–	73	[177]
Ni/lignite	Fixed bed	Corncob	650	50.0 mmol/g	90.0	[178]
Ni/HZSM-5	Fixed bed	Corncob	750	52.8 mmol/g	92.2	[179]
$Ni/La_2O_3/Al_2O_3$	Fluidized bed	Pine wood	600	90%	96.4	[180]
$Ni-Co/\ Al_2O_3$	Fluidized bed	Pine wood	600	92.3 to 50.9%	99.0	[181]
Fe – Mo/ZSM-5	Downdraft fixed bed	Hardwood pellets	850–950	88 to 90 mol%	–	[182]
$PSC-K_2FeO_4$	Two-stage fixed-bed	Peanut shell	800	–	94.9	[183,184]
Ni	Fluidized bed steam gasifier	Toluene	775	52.6 vol%	85.9	[185]

processes spans a broad spectrum, from nascent proofs-of-concept to fully commercialized and operational stages, represented by nine TRLs. Among the various tools to assist in evaluating this maturity, Techno-Economic Assessment (TEA) stands out as a valuable approach. TEA analyses the technical and economic performance of processes and systems, facilitating informed decision-making to enhance overall performance [195]. Common economic indicators used in the techno-economic analyses of biomass gasification include capital expenditure (CAPEX), operational expenditure (OPEX), total capital investment (TCI), production cost (PC), levelized cost of hydrogen (LCoH), break-even price (BEP), net present value (NPV), internal rate of return (IRR) and payback period (PP) [196].

Techno-economic analyses typically adopt two methodologies. The first entails assessing technical and economic performance metrics from prior research, with adjustments made for inflation and currency fluctuations as necessary [197]. The second approach uses standardized simulations with tools like Aspen Plus or Aspen HYSYS to generate mass and energy balances, followed by estimating investment and production costs [196]. In the study of Wang et al. [198], a techno-economic analysis compared coal-to-hydrogen (CTH) and biomass-to-hydrogen (BTH) conversion via gasification as shown in Fig. 17. The simulation results indicated energy efficiencies of 37.82% for CTH and 37.88% for BTH. The gasification unit caused significant energy losses, 64.5% for BTH and 67.4% for CTH. Economically, BTH required higher capital investment and more materials but resulted in lower GHG emissions and production costs compared to CTH. Colantoni et al. [199] assessed the economic feasibility of biomass CHP systems of 100 kWth, 1 MWth and 10 MWth using a bubbling fluidized bed reactor and various Italian biomass types. A Monte Carlo Simulation was conducted to assess NPV sensitivity, identifying biomass cost, syngas production and electricity sales price as key factors. Positive NPV likelihood ranged from 66 to 90%, increasing with plant size.

Okolie et al. [200] conducted a TEA and sensitivity analysis of hydrogen production via supercritical gasification of biomass. Using Aspen Plus v7.3, they designed and simulated a plant processing 170 metric tons/day of soybean straw. The results showed that the production cost was lower than other biomass conversion processes, and a positive NRR of 37.1% indicated profitability. Key factors affecting hydrogen prices were tax rate, raw material cost, and labour cost. Lepage et al. [201] found that the most mature hydrogen production technologies from fossil fuels, such as steam methane reforming (SMR) and coal gasification, have the lowest costs, around US$ 1/kg H_2, due to

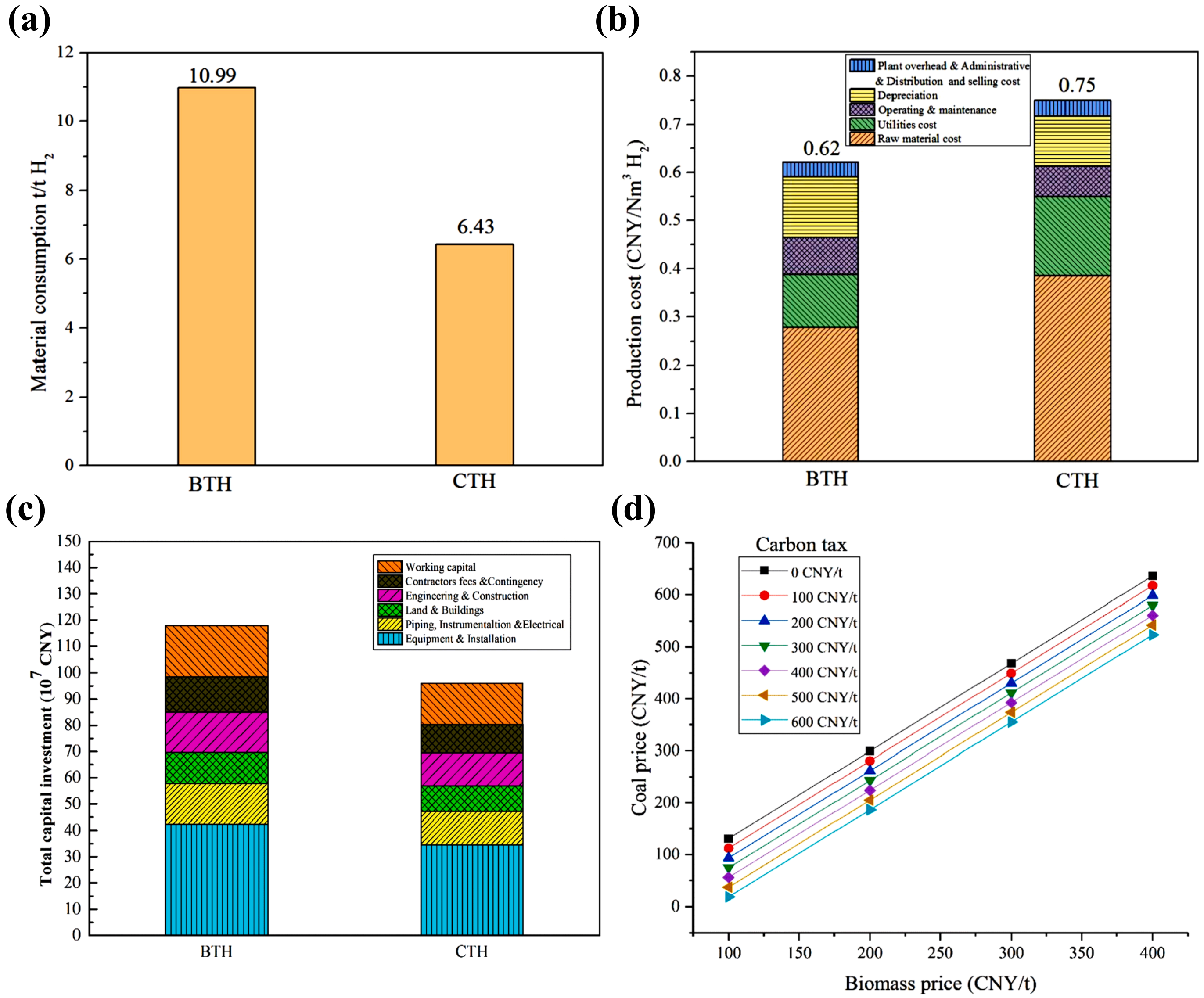

Fig. 17. (a) Material consumption, (b) Production cost, (c) Total capital investment of BTH process and CTH process and (d) Relative cost of biomass and coal under different carbon tax conditions. Reprinted with permission from [198], Copyright Elsevier ©2019.

large plant capacities and low feedstock prices. Among renewable methods, biomass gasification was the most cost-effective, averaging US $ 2.36/kg H_2, compared to dark fermentation, biomass pyrolysis, photo-fermentation and water electrolysis. Incorporating CCS systems into the SMR process increased production costs by 25–30%. Li et al. [202] evaluated the TEA performance of integrating biomass gasification with methane tri-reforming (MTR) to convert syngas CH_4 into CO and H_2. The addition of MTR increased the TCI by 10.97%, mainly due to higher equipment and installation costs. Despite this, the TPC with MTR was 10.12% lower than without it. Although utility costs were 7.4% higher with MTR, raw material costs were 5.26% lower. Payback periods were approximately 4.5 years with MTR and 4.72 years without. The study concluded that integrating MTR with biomass gasification improves the economic and environmental sustainability of hydrogen production.

Emerging studies now include eco-efficiency assessments that evaluate both economic and environmental performance of hydrogen production processes. Al-Qahtani et al. [197] estimated the “real” total cost of hydrogen by adding monetized environmental impacts on ecosystem quality, human health, and resources to the levelized cost. These environmental costs comprised 14–88% of the total hydrogen cost. Steam methane reforming with CCS was the cheapest option due to low production costs and relatively lower greenhouse gas emissions. Biomass gasification was found to be expensive due to significant impacts on ecosystem quality from high land use and water consumption during biomass cultivation. The study concluded that while biomass gasification has potential, its eco-efficiency is highly sensitive to the type and location of biomass feedstock [197]. Integrating carbon capture in fossil-fuel-based gasification systems can double hydrogen production costs, whereas, in biomass gasification systems, it increases costs by 15% or less [196]. Literature suggests that with technological advancements and greater biomass feedstock availability, biomass gasification could surpass conventional methods [203]. Additionally, as the technology matures and plant capacities increase, the cost competitiveness of hydrogen from biomass gasification is likely to improve. Comprehensive assessments, considering economic, environmental and social factors, are essential for evaluating the scale-up potential of biomass gasification for hydrogen production.

9. Social and environmental aspects

The sustainability of technology is typically assessed through four key indicators: environmental, economic, social and technological [204] as shown in Fig. 18. These indicators are interlinked and overlapped and gain importance for sustainability criteria of a technology implementation on a larger scale [204]. As a renewable resource, bioenergy offers ecological benefits such as lower carbon dioxide emissions, enhanced carbon sequestration, local economic growth, reduced biomass incineration and improved air quality [205]. By reducing GHG emissions, bioenergy aligns with SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action) [206]. However, integrating biomass gasification on a larger scaler presents several challenges. Ensuring a reliable and sustainable supply of biomass is crucial, given issues like seasonal variations, land-use changes and competition with other sectors [207]. Additionally, the quality and composition of biomass affect gasification efficiency, making standardization and research essential [208]. While biomass is generally considered carbon–neutral, accurate evaluation of net emissions from gasification systems is needed, including assessing land-use changes, transportation emissions and CO_2 storage leakage through detailed life cycle assessments and carbon accounting [188].

Integrating on a large scale also involves significant technological

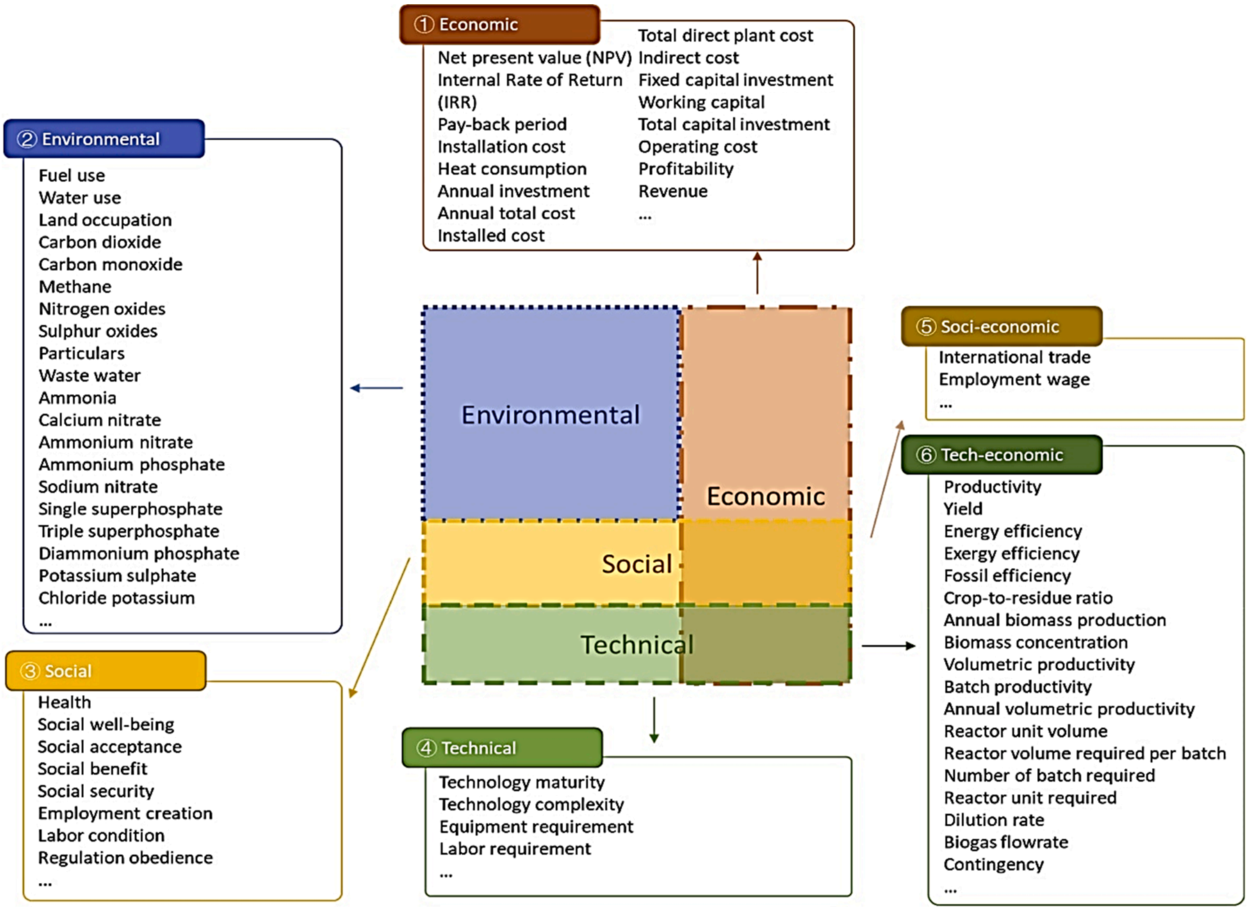

Fig. 18. Sustainability indicators of a technology. Reprinted with permission from [204], Copyright Elsevier ©2020.

and financial challenges, requiring ongoing innovation, research and collaboration. Regulatory and policy variations impact project feasibility and scalability. Addressing public concerns about land use and air quality through transparent communication and environmental impact assessments is essential. Successful implementation also demands secure CO_2 storage, overcoming infrastructure challenges and substantial investment in gasification systems. Additionally, societal perception poses a challenge. Educating the public on its benefits is crucial, as barriers such as inadequate policies, high initial costs and various institutional and market issues hinder adoption. While gasification technologies are pivotal for meeting rural energy needs, their widespread adoption hinges on achieving social acceptability [205].

Planning for sustainable bioenergy crop production involves balancing often conflicting objectives, such as maximizing biomass productivity while maintaining environmental quality. Trade-off analysis is crucial for evaluating these compromises and making informed decisions. This analysis provides a comprehensive view of the socio-economic and environmental factors in bioenergy production, helping identify issues and opportunities for a holistic approach. Ignoring trade-offs can lead to conflicts that compromise the achievement of sustainability goals. Trade-off analysis utilizes various methods to address conflicting objectives [209]. Integrated Assessment Models (IAMs) highlight bioenergy's critical role in achieving net-zero emissions, with its unique advantage of being a carbon-containing renewable fuel [210]. Empirical methods analyze data to identify quantitative relationships, while simulation models explore unobserved relationships. Multi-objective optimization is commonly used to analyze trade-offs in biomass supply chains, balancing conflicting goals to optimize system performance. This analysis ensures that each objective aligns with broader sustainability goals [209]. Experimental studies on conversion technologies are vital for identifying the most effective options.

Predictive analyses using numerical models assess the impact of various parameters and determine optimal conditions for system performance. Life Cycle Assessment (LCA) [ISO 14040, 2006] is a key tool for evaluating the environmental impacts of products throughout their life cycles [211] as shown in Fig. 19. LCA shows that bio-based products generally reduce GHG compared to fossil fuels, it also reveals significant trade-offs, such as eutrophication and biodiversity loss related to biomass cultivation [195]. LCA, while effective for evaluating environmental impacts, has limitations in assessing economic and social aspects of sustainability [205]. Wang et al.[212] critically review LCA of BECCS technologies including biomass gasification. A complete BECCS value chain consists of biomass supply, conversion and CCS, encompassing upstream activities like cultivation, harvesting and transportation, as well as downstream impacts such as decommissioning and waste disposal. These stages also account for land-use changes and infrastructure construction, including bioenergy plants and CO_2 pipelines [212].

10. Biomass gasification in transition to net zero emissions

Numerous nations aspire to achieve net-zero GHG emissions by 2050 to comply with the Paris Agreement's objective of constraining global temperature increases to well below 2 °C, ideally below 1.5 °C, relative to preindustrial levels. Achieving net zero entails equilibrating GHG emissions with their removal from the atmosphere via anthropogenic measures. This necessitates substantial emission reductions across all sectors, alongside the removal of some GHGs through natural mechanisms like afforestation and negative emissions technologies, such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) of CO_2 [213]. Biomass gasification, an emerging technology, is used to produce electricity and syngas on pilot scales and is progressing toward commercial plants. This single-step thermochemical process converts biomass into syngas using a gasifying agent (air/steam/oxygen) at temperatures of 650–1200 °C [5]. Gasification stands out among biomass conversion technologies due to its efficiency, versatile products and low NOx emissions. It offers a way to manage biomass wastes like agricultural residues and helps reduce GHG [214]. For instance, the UK's largest 21.5 MW waste wood gasification plant could reduce GHG emissions by 65,000 tons of CO_2 equivalent annually [215].

Biofuels can reduce reliance on fossil fuels and lower GHG emissions and carbon footprint. Consequently, researchers are optimistic about their potential and have positive predictions for biofuels [216]. Clean fuels like hydrogen (H_2), Fischer-Tropsch liquids (FTL) and synthetic natural gas (SNG) are expected to play crucial roles in future net-zero economies [213]. To optimize biomass fuel conversion into electricity and heat, various gasification system combinations have been explored, including the Integrated Gasification Combined Cycle (IGCC) and

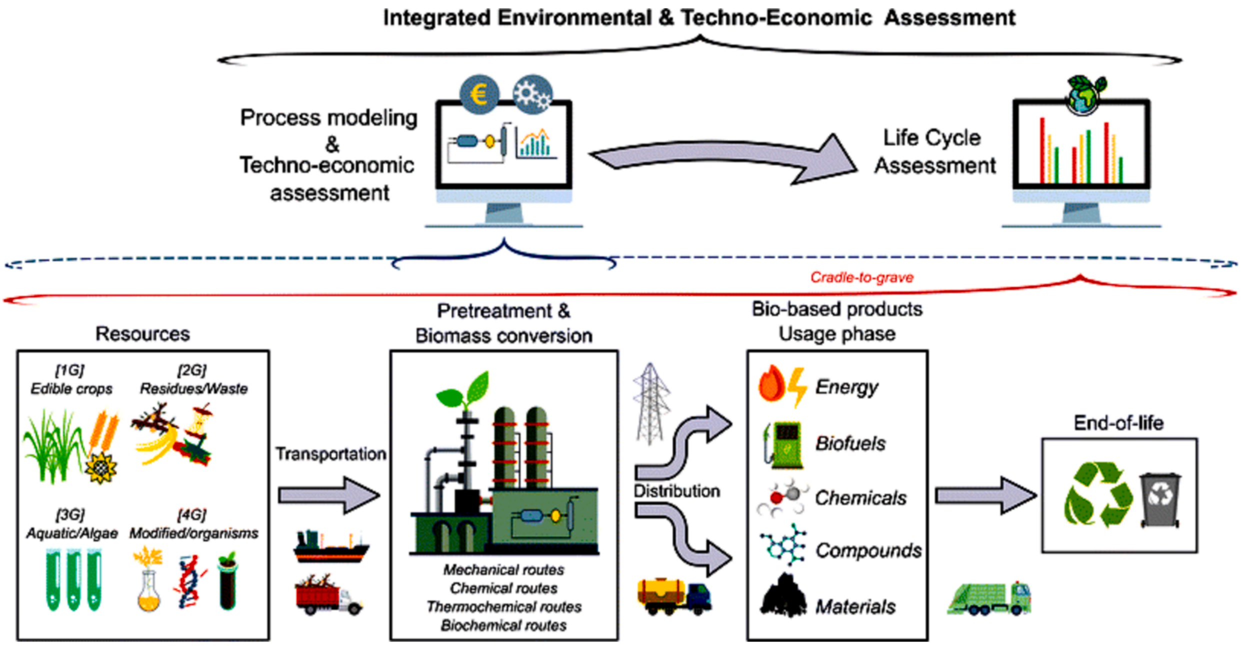

Fig. 19. A combined environmental and techno-economic analysis serves as a methodology for assessing the sustainability of biorefinery value chains. Reprinted with permission from [195], Copyright RSC ©2023.

Biomass in Integrated Gasification Combined Cycle (BIGCC). IGCC integrates gasification/combustion with turbines and generators to convert syngas from coal, petroleum, biomass and wastes into power. IGCC and CHP offer significant CO_2 mitigation benefits, with CO_2 capture rates of 44% and 85%, respectively, reducing emissions by 140 gC/kWh and capturing 200 kgC for a 200 MW power plant [5].

11. Challenges and future outlook

Advancements in biomass gasification have improved efficiency, reduced emissions, and enhanced adaptability. Novel reactor designs, advanced controls, and integrated purification technologies have propelled the field forward. Biomass gasification offers a renewable energy source by converting various biomass inputs into versatile syngas. Syngas can power electricity, heat, and biofuel production, reducing reliance on fossil fuels. It's a greener option, cutting greenhouse gas emissions compared to fossil fuel processes. Effective gas purification minimizes emissions, making biomass gasification environmentally sustainable. However, biomass gasification encounters challenges such as feedstock quality variability, high initial costs and large-scale operational demands, which impede broad adoption. Economic viability can be enhanced by integrating gasification with processes like CHP or syngas utilization. Successful deployment depends on supportive policies, financial incentives, and regulatory frameworks. Governments and industries must invest in R&D, provide financial support and establish conducive regulations. While pilot projects show potential, scaling up requires concerted efforts and collaboration among academia, industry and government.

Utilizing catalysts shows promise for addressing tar challenges, but hurdles remain. Issues like catalyst deactivation and formulation need thorough research. Developing composite catalysts to counter deactivation is crucial. Understanding deactivation mechanisms from impurities in tar requires inquiry. Crafting catalysts with high activity at lower temperatures is essential for energy efficiency. Strengthening catalysts is necessary due to fragmentation. Concerns persist over stability and activity, highlighting the need for improvement. Synthesizing catalysts for effective tar conversion is a key focus. Understanding tar complexity and its effects on catalysts is vital. Maximizing catalyst-biomass contact requires further research into reaction mechanisms across different conditions. Greater endeavours are requisite for advancing steam reforming catalysts. A multifaceted approach that integrates various tactics such as reaction enhancement, catalyst utilization, adsorption, or separation techniques could prove more efficacious for tar reduction in a fluidized bed gasification system. Additionally, addressing logistical challenges in remote areas' power supply can be achieved by deploying biomass power units strategically. Establishing local governing bodies and promoting bioenergy over conventional sources are crucial. Affluent nations should aid developing countries in combating climate change by supporting bioenergy initiatives. Revision of policies and increased research and infrastructure are essential for successful biomass gasification dissemination.

12. Conclusion

This comprehensive review delves into the characteristics and reduction techniques of impurities, a significant challenge in biomass gasification. Understanding impurities formation, composition, conversion and potential removal strategies is essential for optimizing the gasification process and producing a cleaner product gas. Primary tar rearranges into secondary tar at 500 °C, while tertiary tar originates at 800 °C. Tar condenses at < 300 °C, blocking gas pipelines, causing disruptions and effect downstream processes. Optimizing gasification involves adjusting temperature, gasification agent, air/steam ratios and residence time for cleaner product gas. Tar content behaviour varies with gasifier design; updraft fixed bed gasifiers yield higher tar content (around 100 g/Nm^3), than downdraft ones (around 1 g/Nm^3), with a 30–90% reduction. The fluidised bed produces intermediate tar (around 10 g/Nm^3), a mix of secondary and tertiary tar. Circulating bed gasifiers reduce tar by 50% compared to bubbling bed counterparts. Various physical–mechanical methods achieve up to 99% tar removal but may reduce energy conversion efficiency and generate hazardous waste. Thermal cracking, with up to 98% efficiency, requires additional power for high temperatures. Catalytic treatments excel, achieving nearly 100% tar removal. Nickel-based catalysts and natural catalysts like dolomite, zeolites and olivine are cost-effective but show improved efficiency as transition metal supports. Activated char enhances removal efficiency by up to 90% when utilized as support for metal catalysts like Fe, K etc. Furthermore, gasification technology has achieved a TRL of 8–9 and can be successfully implemented on a larger scale. However, biomass gasification systems increase costs by 15% and need further improvements in terms of techno-economic, environmental and societal issues. Future research should prioritize versatile, efficient gasification technologies that accommodate diverse biomass and waste types, with vital attention to durable and easily rejuvenated catalysts in complex processes.

Farooq Sher
https://orcid.org/0000–0003-2890–5912
Saman Hameed
https://orcid.org/0000-0002-9549-6701
Narcisa Smječanin
https://orcid.org/0000–0001-6283–3110
Alexander Chupin
https://orcid.org/0000–0002-0804–8039
Irfan Ul Hai
https://orcid.org/0000–0002-1083–6499
Bohong Wang
https://orcid.org/0000–0003-1206-475X
Yew Heng Teoh
https://orcid.org/0000–0003-1524–5214
Magdalena Joka Yildiz
https://orcid.org/0000–0002-4745–5972

CRediT authorship contribution statement

Farooq Sher: Writing – original draft, Funding acquisition, Data curation, Conceptualization. **Saman Hameed:** Writing – original draft, Investigation, Formal analysis. **Narcisa Smječanin:** Writing – review & editing, Validation, Project administration. **Alexander Chupin:** Writing – review & editing, Visualization, Funding acquisition. **Irfan Ul Hai:** Writing – original draft, Investigation, Data curation. **Bohong Wang:** Writing – review & editing, Resources, Funding acquisition. **Yew Heng Teoh:** Writing – review & editing, Visualization, Investigation. **Magdalena Joka Yildiz:** Writing – review & editing, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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