Chapter

Opportunities and Challenges of Harnessing Biomass Wastes for Decentralized Heat and Energy Generation and Climate Mitigation via Fluidized-bed Gasification Pathway

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Abstract

Biomass wastes offer immense potential as a renewable energy source, holding the promise to replace fossil fuels for heat and energy generation, in particular for decentralized power production. Furthermore, the utilization of biomass promotes circular economy by enabling the conversion of local resources into useful products and energy. However, the conversion of biomass into end-use products and heat/energy is a complex process with multiple pathways, such as fluidized bed gasification, a well-established and efficient method for converting coal and biomass into heat. Despite its merits, this process is currently limited to industrial applications and encounters certain limitations and obstacles. Notably, the low energy density of biomass wastes and downstream pipe contamination from tar and polycyclic aromatic hydrocarbon (PAH) growth poses significant technological challenges. Nonetheless, a roadmap has been developed to guide the widespread adoption of fluidized bed gasification of biomass for decentralized power generation and climate mitigation. This book chapter delves into the opportunities and challenges of fluidized bed gasification as a viable option for decentralized power generation and climate mitigation through biomass waste conversion. The significance of well-crafted policies supporting renewable energy sources and optimizing fluidized bed gasifiers to achieve desirable end products are also emphasized.

Keywords: fluidized bed gasification, biomass wastes, GHG emission reduction, decentralized heat and power, climate change mitigation, circular economy

1. Introduction

Currently, a substantial portion of the world's energy supply is derived from fossil fuels, whose reserves are unsustainable. High carbon fuel consumption and concomitant greenhouse gas emissions are currently the most pressing and well-considered challenges [1]. To address these encounters, renewable energy seems quite promising. Among all, biomass wastes are one of the renewable energy sources which can potentially substitute fossil fuels for heat and energy generation [2]. As biomass waste is virtually everywhere, it is an excellent resource for distributed heat and power generation, which reduces dependence on fossil fuels and central power generation, which is hugely challenged by global energy politics. It also promotes a circular economy as local resources can be converted to useful products and energy [3]. It can also be coupled with carbon capture, and bio-remediation through special biomass sources to have a greater impact on the environment [4]. Also, the utilization of biomass waste such as municipal and agro-industrial waste as feedstocks in large quantities resolves the concerns associated with waste management, aiding to curb environmental pollution and severe health effects [5].

There are various biomass-to-end-use (bio-based products and heat/power) conversion pathways. Thermo-chemical and biochemical conversion of biomass is the major conversion route yielding a wide range of products and subsequent applications. Thermochemical conversion is a widely employed means of biomass conversion through combustion, pyrolysis, gasification, and liquefaction [6]. Among those pathways, gasification is gaining increased attention for its better conversion efficiency, accommodation of a variety of feedstocks, and yield of a variety of products for versatile applications [7]. Fluidized bed gasification is a very matured and efficient coal and biomass conversion pathway mostly limited to industrial applications to date. Due to high solid-to-gas contact and excellent heat transfer in the fluidized bed, it is considered very suitable for controlling operating conditions (such as reaction temperature, residence time, and solid gas heat transfer) and the end product distribution compared to other gasification and thermo-chemical conversion pathways [8]. In addition, it is also suitable for a wide range of feedstocks. **Figure 1** shows a typical gasification process with respect to the operating temperature. Even though fluidized bed gasification is one of the most promising technologies used for the thermochemical conversion of coal and biomass materials, it comes up with challenges and limitations [10]. Particularly, the low energy density of biomass waste and challenges like syngas quality. In terms of heating value and the amount of contaminants like tar, particulates, and heavy metals present in the syngas, the downstream processes like upgrading and cleaning have a direct impact on investment and operational costs. In addition, transporting raw biomass residue over a long distance is not feasible technically or economically because of the very low volumetric energy density of biomass, which may require more fuel energy than it can produce [3].

In a frontier to design optimized fluidized bed gasifiers for typical end-products, experimental and computer models have been extensively employed. Experimental works are highly limited to lab-scale reactors and fail to represent actual-scale gasification processes due to cost and complex processes which makes the experiment difficult. Although computer models are widely employed to simulate the fluidized bed phenomena, it comes with severe limitations as fluidized bed gasification involved complex multi-phase, multi-step, multi-scale processes, which are very expensive to be dealt with in great detail at the same time.

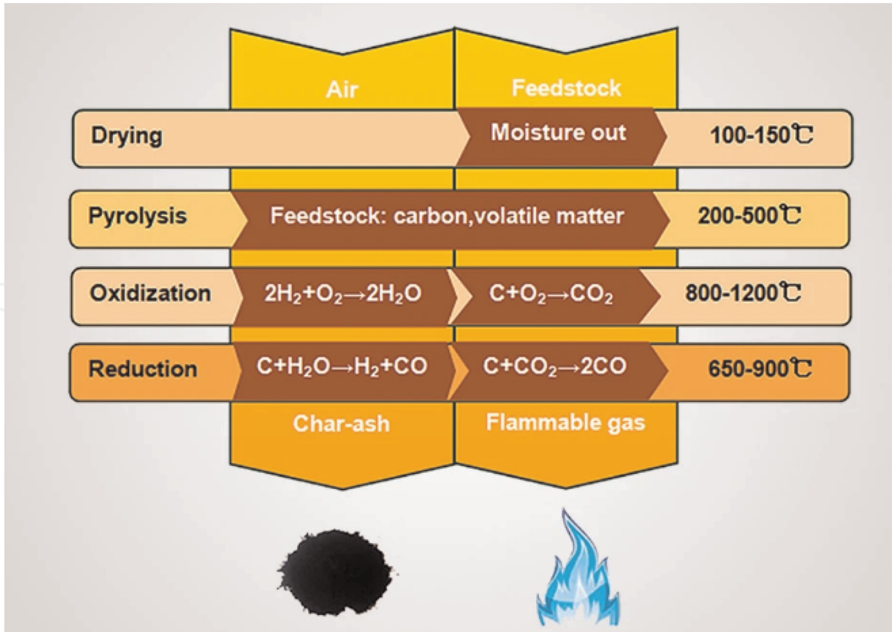

Figure 1.
Typical steps in gasification [9].

In addition, due to a lack of well-formulated strategies and policies towards renewable energy, biomass waste is highly under-exploited, and often times it is dumped and burned in the open air, which has been a common trend in many developing countries. A comprehensive approach combining the technical, economic, strategic, and policy frameworks should be followed to address the existing challenges.

In this book chapter, the opportunities and challenges of the existing fluidized bed gasification technology as a potential candidate for biomass to heat and energy conversion pathways will be discussed.

2. Fluidized bed gasification

2.1 Biomass wastes conversion via fluidized bed gasification

There are several Biomass waste conversion routes to valuable products or heat/power production as summarized in **Figure 2**. The choice of technology depends on the desired end-use, the nature of biomass, resource availability, and other considerations like the techno-economic and environmental aspects [11]. The main technologies employed so far are categorized under thermochemical conversion, biochemical conversion, and extraction leading to a wide range of applications such as heat and electricity generation, bio-oil, hydrogen, and various synthetic chemicals production [8]. Thermochemical conversion is among the widely exploited routes given its versatility in accommodating a wide range of feedstocks, design options, and a wide range of final products and application domains.

A prevailing thermochemical conversion method is biomass gasification as portrayed in red arrows in **Figure 2**, which typically uses a fixed or fluidized bed reactor to convert biomass into gaseous fuels at low to moderate temperatures [12]. Due to its several advantages over fixed bed gasifiers, fluidized bed gasification has garnered increasing attention over the others, in the biomass to heat/power conversion. High mixing and reaction rates, accommodation of various biomass feedstock, and its potential for scaling are the main winning points [13]. The gasification technologies are summarized in the **Table 1** with their typical features, advantages, and limitations.

Gasification usually produces a gas mainly composed of CO and H_2 with energy values between 5 and $20 MJ/Nm^3$ depending on the biomass characteristics, operating

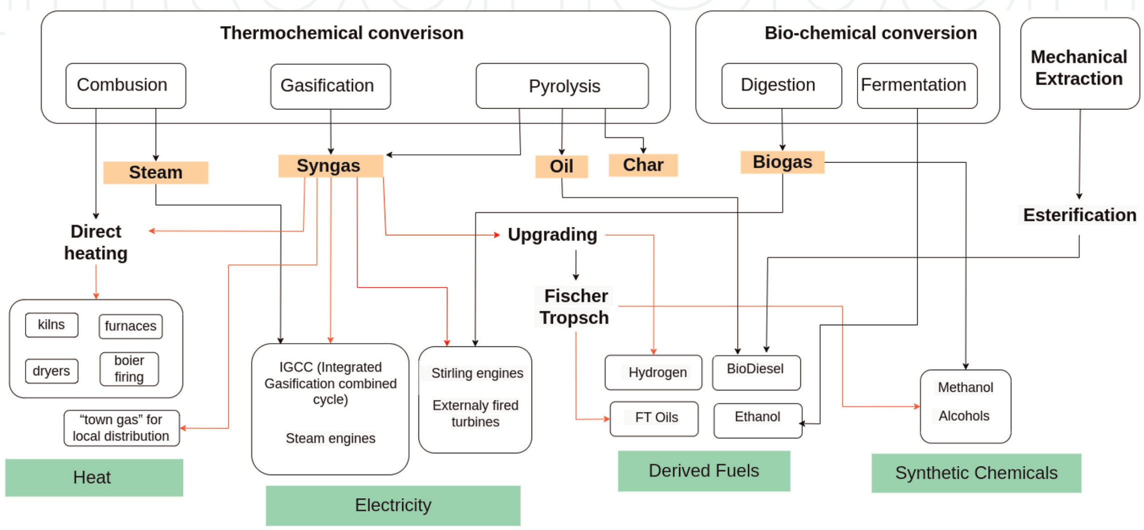

Figure 2.
Biomass conversion routes emphasizing gasification pathways with red arrows (adapted from [6–8]).

Interms of gasifier design	
Bubbling bed	***Features***
	The bed is a two-phase region of bubbles and the emulsion. The fluidizing gas is generally kept in continuous mode, entering through the bottom and exiting through the top [10].
	Pros → moderate investment cost—intermediate control [8]—can handle a wide range of feedstock types and gasifying agents (Air, Steam, and O_2) [8]—a wide range of scale, $10-100 MW$ [8]—carbon conversion efficiency $>90\%$ [8]—Intermediate tar yield [8]
	Cons → low thermal throughput $(1.2-1.6 MW/m^2)$ [8]—feedstock size affects bed hydrodynamics and fine particles are subject to elutriation [8]
	Application → direct heating—combined heat and power (CHP) using internal combustion (IC) engine or gas turbine and heating boilers—biomass-derived fuels via Fischer-Tropsch process [14]
Circulating fluid bed	***Features***
	the solids move in a cycle characterized by thorough mixing and high residence times within the solid circulation loop [10].
	Pros → can handle a wide range of feedstock types, sizes, and gasifying agents (air, steam, and O_2) [8]—highly scalable with $>20 MW$ [8]—carbon conversion efficiency $>90\%$ (better than BFB) [8]—intermediate tar yield [8]—high thermal throughput $(5-7 MW/m^2)$ [8]

Interms of gasifier design	
	Cons → high investment cost and intermediate control [8] ***Application*** → IGCC/IGFC [15]—methanol synthesis [16]
Dual/Twin Fluidized bed	***Features***
	Circulating hot bed material is heated in a separate fluidized bed reactor by combustion of residual biomass char [17]
	Pros → better carbon conversion efficiency [18]
	Cons → complex construction [10]
	Application domain → some commercial combined heat and power (CHP) [18]—gas supply—hydrogen production—synthesis of liquid fuels—other industries [19]
Entrained bed	***Features***
	Powdered fuel ($0.75mm$) is injected into the reactor chamber along with the gasifying agent [10]. It operates at high gasification temperatures (1300–1500°C) [8]
	Pros → carbon conversion up to 100% [8]—very low tar yield [8]
	Cons → suitable for very fine feedstocks and air gasification [8] [20]—suitable for high plant capacity only ($>100MW$) [8]—high investment cost and complex operation control [8, 10]
	Application → suitable for IGCC (integrated gasification combined cycle) plants [10]
Updraft	***Features***
	Fixed bed type. The fuel is fed in from the top, and the gas generated also emerges from the reactor via the top [10]
	Pros → low investment cost [8]—very easy control
	Cons → sensitive to feedstock type and size unlike fluidized beds but better than downdraft [8]—very high tar yield [8]—suitable for plants upto $20MW$ only [21]—low power throughput ($1-2MW/m^2$) [8]
Downdraft	***Features***
	Fixed bed type. Biomass is fed in from the top and drops downwards, while air is injected from one side [10]
	Pros → Low investment cost [8]—very easy control—produces low tar gas [22]—has a carbon conversion efficiency of 93–96% [8]
	Cons → very sensitive to feedstock size and type [8]—suitable for low moisture content [22]—suitable for small-scale plants up to $5MW$ [21]—low power throughput ($1-2MW/m^2$) [8]
Interms of heating	
Direct heating (auto-thermal)	***Features***
	Gasifying agent is supplied along with the fuel creating an oxygen-deprived environment.
	Pros → reduced operation cost—reduced capital cost
	Cons → NA
Indirect heating (allothermal)	***Features***
	Heat is supplied using heat exchanger

Interms of gasifier design		
		Pros → better cold gas efficiency than direct heating [23]—higher gas quality (heating value of $12-20 MJ/Nm^3$)—lower tar and char ***Cons*** → requires external heating usually using an external steam source [24]
	Plasma	***Features***
		Inert gas is passed through the high-energy electric arc and heated to 1500–5000° C. Organic components are converted to gas while inorganic components are converted to virtuous slag when the biomass comes in contact with the plasma arc [25]
		Pros → can be used with organic MSW (municipal solid waste), and other wastes such as paper, plastics, glass, metals, textiles, wood, rubber, etc. [10]
		Cons → still under study not yet in commercial stage
Interms of operating pressure		
	Atmospheric	***Features***
		Operates at operating pressure
		Pros → a more economical design
		Cons → NA
	Pressurized	***Features***
		Gasification pressure between 5 and $40 bar$
		Pros → higher energy conversion efficiency—higher exergy efficiency [24]
		Cons → higher operating cost
Interms of gasifying agent used		
	Air gasification	
		Pros → low cost [21]—better plant safety [26]
		Cons → produces a low heating value fuel gas, generally from 4 to $7 MJ/Nm^3$ [27] [21]
	Steam gasification	***Pros*** → produces a gaseous secondary energy carrier with a calorific value typically in the range of $12-14 MJ/Nm^3$ [28]
		Cons → NA
	Oxygen gasification	***Pros*** → produces a higher heating value fuel gas, $12-28 MJ/Nm^3$ [29]—direct oxygen-blown gasification suitable for large-scale Bio-SNG production [24]
		Cons → high cost of using O_2 [30] [21]
	Combined gasification	***Features***
		steam–air, steam-oxygen, steam–air-oxygen and oxygenated air
		Pros → can make a tradeoff between cost and performance
		Cons → NA

Table 1.
Summary of features of gasification systems.

conditions, and gasifying agent used [2]. Integrated with a gas turbine, boiler, or steam turbine it can be a viable biomass-to-energy conversion component in heat, power, and combined heat and power systems. Syngas can also be an alternative fuel

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in modified internal combustion engines for electricity generation. Small and medium-scale Combined Heat and Power (CHP) systems also known as 'co-generation' are used to convert biomass into electricity while extracting waste heat, a promising application for commercial buildings such as hospitals, schools, or office building blocks but can also be used for decentralized power generation in remote and rural areas [31]. For existing coal plants, burning solid biomass in traditional power plants alongside coal, in a process known as 'co-firing', is a cost-effective, more efficient, and clean option with only minor technical adjustments. Caputo et al. [11] calculated and compared the overall system efficiencies for ï¬,uidized bed combustor with steam turbine cycle and fluidized bed gasifier with combined gas-steam cycle in a black-box model using literature data. The system with the fluidized bed gasifier has an efficiency between 36 and 45% while the former has an efficiency between 25 and 28% for a power scale between 5 and 50MW.

2.2 Fluidized bed performance indexes and important process parameters

The knowledge of performance indexes of any energy conversion system is crucial to determine plant size, investment cost, techno-economic feasibility, and environmental impact. The overall plant performance is the sum of the upstream, downstream, and gasification in-bed performances considering the gasification reactor as the powerhouse of the plant. The upstream process may require biomass feedstock treatment and in the downstream, there are auxiliary components such as gas cleaning units, boilers, engines, and turbines, depending on the plant's application. The commonly used performance indexes in fluidized bed gasification are gas yield, the high heating value of gas, cold gas efficiency, carbon conversion efficiency, and thermal efficiency [31, 32]. All performance indexes are attributed to the in-bed gasification process, except the thermal efficiency is calculated for the whole plant.

Gas yield

$$\gamma = \left(\frac{Q_{syngas}}{Wb(1 - X_a)}\right) \tag{1}$$

where Q_{syngas} is the flow rate of syngas (producer gas) (Nm^3/h), Wb is the mass flow rate of biomass (kg/h), X_a is the ash content in the feed (on a dry basis).

High heating value

$$HHV\left(MJ/Nm^3\right) = \sum HHV_i x_i \tag{2}$$

where x_i (vol%) and HHV_i (MJ/Nm^3) represent the volumetric percentage and the higher heating value of each component in the dry product gas (mainly CO, H_2, and CH_4 in gasification).

Cold gas efficiency

$$\eta_{CG} = \frac{M_{syn} \times LHV_{syn}}{M_{biomass} \times LHV_{biomass}} \tag{3}$$

where M denotes mass.

$$LHV\left(MJ/Nm^3\right) = \sum LHV_i x_i \tag{4}$$

where x_i (vol%) and LHV_i (MJ/Nm^3) represent the volumetric percentage and the higher heating value of each component in the dry product gas (mainly CO, H_2, and CH_4 in gasification).

Carbon conversion efficiency:

$$\eta_C = \frac{C_{syngas}}{C_{bio}} \times 100\% \tag{5}$$

where C_{syngas} is the total carbon amount in the syngas, (kg) and C_{bio} is the total carbon amount in solid fuel, (kg).

Thermal efficiency

$$\eta_{th} = \frac{P_{NET}}{M_{biomass} \times LHV_{biomass}} \tag{6}$$

where P_{NET} is the net thermal power output of the plant, $M_{biomass}$ is the biomass feed rate and $LHV_{biomass}$ is the lower heating value of the biomass.

The performance indexes of a gasification system are affected by a number of factors [33] such as biomass characteristics, temperature, pressure, residence time, catalytic effects (of catalytic bed material and ash), and type and ratios of gasifying agents used.

2.2.1 Biomass characteristics

Biomass residues are products of forestry, agricultural, municipal, and industrial waste and have significant variations in their physical, chemical, and morphological characteristics [34]. Biomass is characterized by its elemental composition (ultimate analysis), moisture content, fixed carbon content, ash content, heating value, density, porosity, and thermal conductivity. The heating value and composition of the product gas depend on the biomass type along with other process parameters. Also, the amount of tar, particulates (ash and elutriated char), and other impurities like heavy metals, are concerns of careful choice of gasification technology and in-bed process optimization and/or cost of downstream cleaning of gas. In the case of lignocellulosic biomass, the main representative building blocks are cellulose, hemicellulose, and lignin. Since these constituent species follow distinct kinetic pathways in the devolatilization step, their proportion in the biomass affects the product distribution. Therefore, the performance of a biomass-based conversion system is hugely dependent on biomass characteristics. Gonzalez et al. [32] studied the effect of biomass characteristics on different performance indexes using 10 different biomass residues. The results suggest a positive correlation between VM, C content, and HHV_{bio} to the combustible gas concentration, calorific value, gas yield, and energy yield of the product gas, while the H_2 concentration is more favored with the H/O ratio of biomass. The reactivity of biomass is affected by the inorganic content present, which in turn affects the carbon conversion efficiency [34]. Also, alkaline is found in some lignocellulosic biomass, which reacts with bed material causing agglomeration [35]. In addition, the amount of ash in the biomass can impact the plant's operating cost due to stringent gas cleaning requirements in some applications [34].

2.2.2 Gasifying agent

The choice of gasifying agent affects the performance and economic aspects of fluidized bed gasification. Syngas heating values typically range between 4 and 7, 10–18, and $12 - 28MJ/Nm^3$ when air, steam, and oxygen are used as gasifying agents respectively [29]. In another study, a simple directly heated fluidized bed air gasification delivers syngas having low heating value $(4 - 6MJ/Nm^3)$ and high tar content $(10 - 40g/Nm^3)$ [13]. Alternatively, syngas with higher heating values $(10 - 40g/Nm^3)$ can be obtained when oxygen and steam are mixed as gasifying agents for a similar gasifier design [36]. It is also demonstrated that a medium heating value $(10 - 15MJ/Nm^3)$ gas can be produced in a dual bed gasifier using steam and air [37].

The high amount of nitrogen dilutes the gas resulting in a considerably lower heating value of yield gas when air is used as a gasifying agent. Steam gasification has the advantage of maximizing hydrogen production via water gas shift reaction $(H_2O + CO = > CO_2 + H_2)$. But the resulting yield gas has lower quality in other performance indexes. As per a report on steam gasification in a circulating fluidized bed there was a decrease in heating value, gas yield, carbon conversion and an increase in tar yield [29]. Oxygen can be an excellent gasification agent as it results in high gas yield, a high heating value of gas, and less tar yield due to high reaction rates. The limitation is the high cost of oxygen production and operation costs [12]. Oxygen is a by-product of green hydrogen production via electrolysis. As a result, the availability of such plants within a reasonable distance from gasification plants can create an affordable supply of oxygen given that there are no other competing interests such as medical use of oxygen.

2.2.3 Equivalence ratio

The equivalence ratio[1] is one of the most important operating parameters. Higher ER favors gas yield but decreases CO, CH_4, and H_2 production and increases CO_2 production [29]. The higher the ER the higher the gas yield as it promotes oxidation and carbon conversion. The heating value of the gas is related to the amount of CO, H_2, and CH_4 [31]. High ER results in lower heating value product gas because more CO_2 and N_2 dilute the combustible gas species. Previous studies demonstrate that lower ER is desirable but too low ER means reduced temperature and the optimum value of ER, usually between 0.2 and 0.4 [38] needs to be maintained. If tar is a concern in the application of the producer gas, a higher ER is desirable (0.3–0.4 [38]) so that the reaction operates at a higher temperature, which favors tar cracking [33]. The response surface method which is a statistical technique that employs regression analysis based on mathematical relations is used to optimize values of input factors like temperature and equivalence ratio for optimal system performance [39].

2.2.4 Steam to biomass ratio

Steam is used as a gasifying agent for improved gas yield, LHV, and carbon conversion efficiency [33]. Water gas shift $(CO + H_2O \rightarrow H_2 + CO_2)$ reaction is

[1] Equivalence ratio is defined as the ratio of actual air to fuel ratio to stoichiometric air to fuel ratio in this chapter's context

favored for the SBR range of 1.35–4.04, which increases the H_2 and CO_2 fraction in the producer gas [33]. Due to the increased yield of H_2, steam gasification is very suitable for H_2 production. When the SBR increases more than the optimum, the reaction temperature reduces due to too much low-temperature steam [40].

2.2.5 Temperature

Bed temperature is one of the predominant parameters affecting the reactions in the gasification process [35]. The chemical kinetics of multi-phase and multi-step reactions in the gasification process is governed by the Arrhenius law of rate constant, which defines the temperature dependence of reactions. As a result, temperature plays the main role in deciding the output gas distribution and the gasifier performance. In a fluidized bed, the temperature remains almost constant due to the high thermal inertia of the bed material. The wide range of operating temperature in fluidized bed gasifiers is between 700 and 1000°C [41]. Pooya et al. [35], studied the effect of operating temperature between 650 to 1050°C, on the gasification of two different biomass in a BFB and the increasing temperature is in favor of gas yield, HHV_{gas}, carbon conversion efficiency, and cold gas efficiency. A higher reaction temperature is in favor of high carbon conversion and tar cracking, which means lower tar and char in the producer gas [33]. However, the gasification temperature is limited by agglomeration and sintering of bed material and ash [13]. Therefore, applications, such as gas engines, turbines, fuel cells, and conversion of gas for the synthesis of fuels or chemicals, need extensive and costly gas cleaning [42] as the temperature is usually kept below 850°C in typical fluidized bed gasifiers.

2.2.6 Bed material

In fluidized bed gasification, the bed material is used as a mixing and heat transfer medium and desirably has high thermal inertia to maintain a fairly uniform temperature in the bed [43]. It has high thermal inertia enough to maintain a nearly constant temperature throughout the bed. The secondary effect of bed material could be acting as a catalyst in the case of catalytic beds, which influences the reaction rates of typical reactions involved in turn affecting the species distribution of yield gas. Some literature reported insignificant tar produced when the catalyst Rh/CeO2/SiO_2 is used in low-temperature gasifications[29, 44]. Gallucci et al. [4] conducted a lab-scale assessment of four different catalytic bed materials (olivine, k-feldspar, kaolinite, and calcite) on their potential for emission reduction of heavy metals and pollutants from PABR (plant-assisted bio-remediation) plant biomass. Several papers reported that Dolomite is an effective catalyst for tar-cracking and enhances gas yield [45, 46].

2.3 Biomass potential via gasification

Biomass resource potentials are large enough to deliver about a quarter (i.e. $200 - 300EJ$) of the world's future energy supply [3] during the century. The share of biomass in the global energy mix has grown from 4% in 2004 to 7.7% in 2013 (which is about 65% share among the renewables) [2], and 10% in 2018 (two-thirds in developing countries) [47]. The sum effect of factors like biomass availability, logistics, technologically feasible options, and policies is what decides the extent of effectiveness of the use of biomass as a competitive energy resource [48]. The primary step for the efficient development of a biomass conversion system is the quantification and energy-potential characterization of the available biomass with respect to the desired application [49]. Jaswinder et al. [48], studied the biomass potential, challenges, technological options, and government policies towards promoting biomass use in decentralized power generation in the Indian context.

2.3.1 Technical potential of biomass

Estimation of the biomass potential that can be utilized for heat power and biomass-derived fuels is a very important step. The potential of biomass is estimated from the annual main production (P_i) and the product-to-residue ratio (R_j) when agro-industrial wastes are considered for utilization [49]. The subscript i denotes the main biomass while the subscript j denotes the residue from its main biomass source more than a single residue can be produced from the main biomass source. The moisture content (MC_j) and low heating values (LHV_j) of the biomass define the theoretical energy potential. Availability factor A should be taken into account in order to estimate the technical energy potential of a biomass (QT_{ij}). In a black-box approach, the gasification system potential can be calculated considering the yearly operational hours H, gasification reactor efficiency ($\eta_{gasific}$), and the generator efficiency (η_{gen}). The heating values and other important characteristics of biomass residues used in thermochemical conversion are summarized in **Table 2**.

Biomass potential from annual main biomass production: $B_{ij} = P_i.R_j$.
Theoretical energy potential of each biomass: $Q_{ij} = B_{ij}.(1 - MC_j).LHV_j$.
The technical energy potential of each biomass: $QT_{ij} = Q_{ij}.A$.
Gasification potential of each biomass: $QG_{ij} = QT_{ij}.H.\eta_{gasific}.\eta_{gen}$.
Regional energy potential: $\overline{Q} = \sum Q_{ij}$, $\overline{QT} = \sum QT_{ij}$, $\overline{QG} = \sum QG_{ij}$.

Hiloidhari et al. [63] used this methodology to estimate India's biomass potential but not limited to gasification only. 686 MT [64] of biomass production with 34% surplus, and can roughly produce 23 GW [29] of power equivalent to the 17% of India's total primary energy demand. The case of India's biomass potential is reported in various papers.

Following the same methodology a 2017 paper [48] estimated India's biomass potential to be 30GW of electricity from all the surplus crops considering availability between 28% and 48% from the surplus residue of 223MT, rice husk, bagasse, and sawdust being the most abundant ones. The annual operation hours are considered as 6570$h/year$ whereas the average lower calorific values, lowest thermal efficiency, and average energy requirements for selected feedstocks (Rice, Wheat, Coarse cereals, Total Cereal, Cotton, Sugarcane) are considered. The installed capacity of bio-energy in India as of 2017 was only 5GW, which is about 17% of its calculated potential.

3. Opportunities

3.1 GHG emission reduction and climate mitigation

According to the International Energy Agency, by 2019 fossil fuels were responsible for 32.1 gigatonnes of CO_2 emissions [65]. Additionally, it predicted that by 2030,

Biomass	Proximate analysis (wt, %)				Ultimate analysis (wt, %, db)					HHV (MJ/kg)	Refs.
	VM	FC	MC	Ash	C	H	O	N	S		
Distilled grain	—	—	13.84[db]	5.84[db]	49.93	7.26	36.45	5.31	1.04	27.2	[50]
Olive kernel			4.59	3.46	48.59	5.73	44.06	1.57	0.57	20	[51]
Corn cobs			7.1	5.34	46.3	5.3	42.19	0.57	0	17.9	[52]
	71.21	16.11	9.71	2.97	40.22	4.11	42.56	0.39	0.04	16.65[a]	[43]
Sunflower stalks			40	3	52.9	6.58	35.9	1.38	0.15	20.8	[52]
Rapeseed stalks			5.86	3.95	45.52	5.53	48.37	0.58	0	16.8	[53]
Corn stalks			0	45.53	6.4	6.15	41.11	0.78	0.13	17.8	[52]
Pine				0.37	52.1	6.36	41	0.07	0.05		[8]
Pine saw dust	82.29	17.16	db	0.55	50.54	7.08	41.11	0.15	0.57	20.54[a]	[54]
Oak				1.29	49.9	5.98	42.6	0.21	0.05		[8]
barley straw				4.95	42.9	5.53	45.5	0.56	0.25		[8]
MSW				12	47.6	6	32.9	1.2	0.3		[8]
Sewage sludge			85	37.5	32.6	4.5	18.9	4.38	1.69		[8]
Cotton gin trash	71.20[db]	15.78[db]		13.02[db]	39.3	5.43	40.49	1.44	0.34		[55]
Saw dust	76.1	8.9	14.6	0.4	44.96	5.83	45.5	3.1	0.61	17.12[db]	[35]
	70.4	17.9	10.4	1.3	46.2	5.1	35.4	1.5	0.06	18.81[a]	[35]
Empty fruit bunch	79.34	8.36	7.8	4.5	43.52	5.72	48.9	1.2	0.66	15.22[db]	[35]
Cedar wood	80–82	18–20	db	0.3	51.1	5.9	42.5	0.12	0.02	19.26[a]	[56]
Olive oil residue	76	19.4	9.5	4.6	50.7	5.89	36.97	1.36	0.3	21.2[a]	[57]
Rice husk	73.8	13.1	12.3	0.8	45.8	6	47.9	0.3		13.36[a]	[58]
Rice straw	65.23	16.55	5.58	12.64	38.61	4.28	37.16	1.08	0.65	14.4[a]	[59]
Spruce wood pellet	74.2	17.1	8.4	0.3	49.3	5.9	44.4	0.1		18.5[a]	[60]
Coffee husk	74.3	14.3	10.4	1	46.8	4.9	47.1	0.6	0.6	16.54[a]	[58]
Coffee ground	71.8	16.7	10.5	1	52.97	6.51	36.62	2.8	0.05	22[a]	[61]
Sugarcane bagasse	67–70	28.7–30.7	db	1.26	48.58	5.97	38.94	0.2	0.05	19.05[a]	[44]
Wheat straw	75.8	18.1	db	6.1	46.1	5.6	41.7	0.5	0.08	17.2[a]	[62]

[a]given in lower heating value (LHV), [db]given in dry basis.

Table 2.
Some of the Biomass residues used in thermochemical conversion pathways.

emissions would be around 42 gigatonnes with the current global trend unless climate agreements are implemented with stringent measures [65]. It is critical to abide by the 2015 Paris Agreement that states global temperature rise should not exceed above 2°C from the pre-industrial levels in order to combat the potentially catastrophic global climate change threat [66]. In accordance with this aim, the EU under the 2030 climate and energy framework plans GHG emissions reduction by 40% through increasing the share of renewable energy by 27% [67]. Resource and environmental sustainability measures primarily involve renewable energy production [6].

Burning of biomass is regarded as carbon neutral (also written in EU legislation [2]) because carbon is re-absorbed during the growth of biomass through photosynthesis where CO_2 and H_2O are converted to glucose and O_2 as depicted in **Figure 3**. A briefing on EPRS(European Parliamentary Research Service) discussed the opportunities and challenges of biomass use for electricity and heat with regard to GHG emission, resource availability, environment, and human health [2]. It outlined that biomass thermochemical conversion for heat and power generation has as high as up to 70% savings in GHG emission in some cases, but is influenced by factors like feedstock type, transportation, and conversion efficiency. In order to compute CO_2 savings and effective emission, the IPPC European Directive put CO_2 emission factors of $0.43 kg/KWhCO_2$ for European energy mix for electricity generation (40% coal, 30% gas, 30% non-fossil) and $0.23 kg/KWhCO_2$ for European fuel mix for thermal applications (50% gas, 40% oil, 10% coal) [68]. **Table 3** shows the commitment of some exemplary countries, EU, and worldwide in terms of the total installed bio-fuel capacity.

Biomass has been utilized for millennia and simply utilizing it does not guarantee sound benefits over other alternatives. In fact, the traditional use of biomass is very

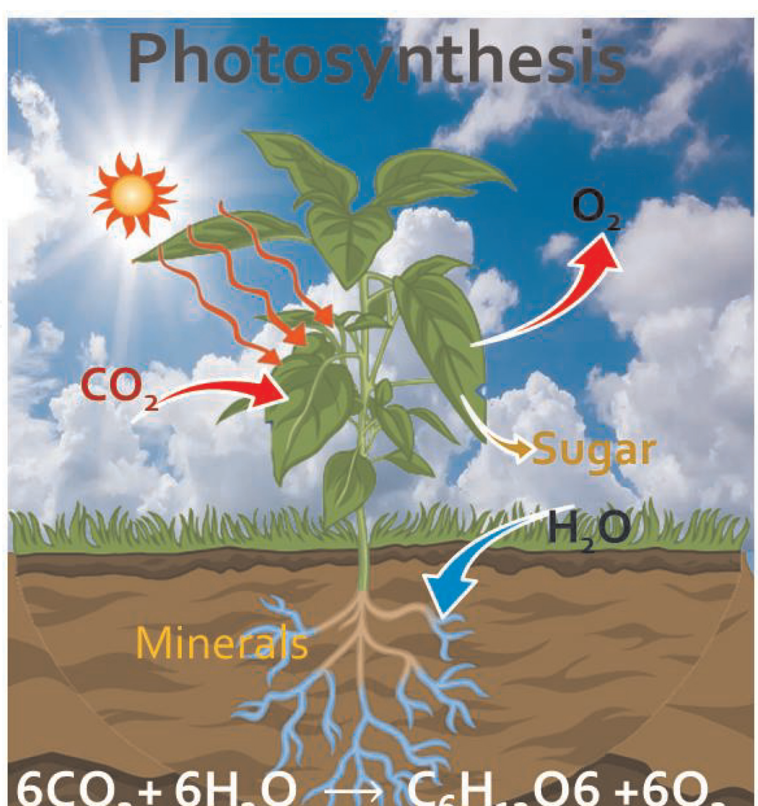

Figure 3.
Carbon cycle via photosynthesis.

Country	Total bio-fuel capacity	Year	Refs
UK	8.8 TWh (25% of total renewables energy	2019	[69]
Denmark & Finland	15% of total electricity production		[70]
Sweden, Austria, Estonia, Belgium, Italy, and Brazil	6 to 8% of total electricity production		[70]
Germany	49.1 GW	2014	[48]
China	17.8 GW	2018	[71]
US	16.2 GW	2018	[71]
India	10.2 GW	2018	[71]
Japan	4.0 GW	2018	[71]
EU	42 GW	2018	[71]
Global	93 GW (433 TWh production)	2014	

Table 3.
Bio-fuel installed capacities of countries, EU and global.

inefficient and can cause adverse effects on air quality and human health [2]. According to a 2017 World Energy Outlook special report [72], a third of the world's population (2.5 billion people) still traditionally serves with solid biomass, which is estimated to cause 2.8 million premature deaths annually due to indoor air pollution. Clean and efficient utilization of biomass with proven technologies like fluidized bed gasification is a promising technological solution for achieving GHG emission reduction and climate mitigation.

Biomass residues constitute municipal waste significantly, especially in rural and developing countries. The global municipal waste production in 2016 is 2.01 billion tonnes which is projected to grow to 2.2 billion in 2025 and 3.4 billion in 2050, according to World Bank statistics [73]. Out of which the trash-derived biomass accounts for 44% [26].

Direct and inefficient burning of biomass for heat and the production of charcoal is a common bio-energy utilization trend in developing countries. Wood, straws, cow dung, and other biomass residues are used for cooking, space heating, and lighting which accounts for about 30.7EJ and another 20 to 40% for informal sectors including charcoal production [74].

Potential deployment levels of bioenergy by 2050 could be in the range of 100 to 300EJ [3]. In sub-Saharan Africa alone, biomass has an outstanding potential of about 15,000MW from just 30% of residues from agricultural crops and forest logging residues [75]. However, there are large uncertainties in this potential such as market and policy conditions, and strong dependence on the rate of improvement in the agricultural sector too [3].

3.2 Distributed heat and power generation from local resource

Biomass conversion via fluidized bed gasification is a very good candidate for distributed power and heat generation. Biomass conversion is way more cost-effective when it is done locally than transported a long distance. In 2015, 72% of energy consumption for space heating and 64% for hot water comes from fossil fuels, and biomass share is about 12% [76]. Waste biomass for heating can fit here well to reduce dependency on fossil fuels. Once commercial, biomass gasification can be a cutting-edge technology for distributed energy generation. This in turn contributes to local income opportunities and green and sustainable development. Developing the local economy by adding value to local resources and reducing dependency on imported sources of energy access in many sustainable development schemes [3].

Biofuels are garnering attention as a promising renewable energy source and a business opportunity for rural communities by cutting fossil fuel demand and reducing greenhouse gas emissions [77]. Affordability, reliability, and sustainability of energy production in rural areas can be guaranteed by decentralized, small-scale systems owned by the local community [1].

As an interesting approach for biomass energy conversion, fluidized bed gasification technology has attractive features for distributed heat and power applications such as [3, 78]:

- Clean and sustainable conversion of local resources resulting in emission reduction and related incentives and government subsidies.

- Ability to handle a wide range of variety of biomass residues

- Techno-economically competitive small and medium-scale applications by avoiding hurdles related to biomass residue processing, storage, and transportation

- Fossil fuel substitute and independent energy access aside central grid

- Deployment of small and medium enterprises in the supply chain in agriculture and forestry

3.3 Circular economy integrating waste management and bio-products supply chain

A circular economy principle is based on closing the life cycle of a renewable resource [79] by extending its value through exploiting its waste. Local farmers can generate additional income by providing biomass fuels for small local power plants [3]. The circular and bio-economy structures are complementary in terms of maintainability and resource efficiency objectives [26]. The global bio-economy plans place a premium on the sustainable management of organic resources to ensure asset viability and biomass sustainability [80]. Such a circular bio-economy will demand the development of biorefineries in addition to enhanced sustainability measures [81]. PABR (Plant assisted bioremediation) plants are being researched for thermo-chemical conversion via catalytic fluidized bed gasification, which has the advantage of biomass being recycled in a sustainable way that complies with the circular economy principles [4] [2]. Several studies have demonstrated that comparable syngas quality can be produced from PABR plants in an FBG and the heavy metals are left in

[2] PABR (Plant assisted bioremediation): is a technique to recover soil contaminated by heavy metals and pollutants using plants' potential to extract them

the ash with the aid of catalytic beds [4], which maximizes the positive impact of the plant during its lifecycle.

3.4 Benefits attributed to carbon taxes and incentives

A carbon tax would give stakeholders in the biomass conversion projects, an incentive in return to efficiently reduce emissions of carbon dioxide and other greenhouse gases. Economically, biomass, as a renewable source of energy, attracts various tax benefits from many governments [82]. The steps taken by the EU such as decarbonization (20% GHG emission reduction) and significant renewable energy usage (20% increase) are among the most exemplary with a commitment of 20% upsurge in energy effectiveness by 2020 from 1990 levels [83]. Article 4 of the Directive (EU) 2018/2001 of the European Parliament and of the Council of 11, lists the support schemes for energy from renewable sources [84].

4. Existing challenges

4.1 Technical/technological bottlenecks

One of the key challenges in developing commercial advanced waste gasification technologies is to improve the quality of the syngas produced, making it suitable for a range of applications, including energy generation in gas engines or turbines, hydrogen production, or chemical feedstock [10]. Compared to traditional fuels, syngas from biomass gasification has a low heating value. During gasification, various compounds are released, such as tars, heavy metals, halogens, and alkaline compounds, which can cause both environmental and operational issues. Generally, the acceptable limit for tar is around $50 - 100\ mg/Nm^3$. While the amount of tar is important for engine applications, the dew point temperature of the tar is more crucial [13]. The heavy polyaromatic hydrocarbons primarily determine the dew point temperature of the total tar, even in small quantities.

As per recent research, both primary and secondary tar removal/reduction techniques are being widely used for advanced waste gasification technologies. Secondary methods like thermal or catalytic tar cracking and mechanical methods such as the use of cyclones, ceramic, fabric, or electrostatic filters, and wet scrubbers have been found to be highly effective in most cases, although they may not be economically feasible and can be particularly complex when very low tar content is required [85]. In-bed methods, which include the adequate selection of main operating parameters, use of proper bed additives or catalysts, and gasifier design and process optimization, are gaining more attention for waste gasification since they can significantly reduce the need for downstream cleanup [86].

Some in-bed tar treatment techniques are [13]:

- **Secondary air**: Secondary air in the freeboard contributes to more oxidation and reforming of water-soluble heterocyclic tars.

- **High-temperature gasification**: A recent experimental study on rice husk gasification [87] showed that non-catalytic high-temperature fluidized bed gasification yields higher heating values ($HHV = 3.6 MJ/Nm^3$ and

$LHV = 3.2MJ/Nm^3$), higher carbon conversion efficiency (91.6%), higher thermal efficiency (75%), higher gas yield ($2.7m^3/kg$) and reduced tar + SPM (solid particulate matter) ($0.33g/Nm^3$). But the upper ceiling of the working temperature (900^0C in this case) is limited by the sintering of ash problem as rice husk has high ash content (18–20% in this case).

- **Narrowly optimized process**: 2–3 ring Light PAH and Heavy PAH require a narrow range of operating conditions of ER, gasification agents, catalysts, and biomass throughput. In a pilot-scale two-stage circulated fluidized bed process using an oxygen-steam gasifying agent, the tar yield was minimized to as low as $1.83g/Nm^3(db)$, in the optimum operating condition ($SBR = 0.15$ & $ER = 0.3$) [12].

- **In-bed catalysts**: In-bed catalysts such as calcined limestone, dolomite, and olivine sand and, less frequently, Ni-based or other metallic catalysts influence the tar cracking/reforming reactions.

In addition to tars, unwanted products in the produced gas (dust, fry ash, tars, ammonia, sulfur compounds, and others) pose a serious problem in the heating or power generation components of the plant and may need to undergo intensive gas cleaning which results in higher plant investment and operation costs [10]. Maximizing gasifier performance and obtaining high-quality fuel is also a very important consideration as it affects the overall technical and economic feasibility of the biomass conversion system. Still, further development and optimization are required to maximize CCE, thermal efficiency, and CGE and minimize tar, char, and ash in the producer gas [3].

4.2 Biomass availability and logistics

The collection, storage, and transport of biomass need to be carefully evaluated as biomass have a poor volumetric energy density, and transporting it at a cost of high energy density fuel (fossil fuels) may not be worth the benefit. Even in the practical scenarios, processing, handling, and transporting biomass from production sites to conversion plants may contribute 20 to 50% of the total costs of bioenergy production [3, 88].

The wide range of power production scale of fluidized bed gasification ($1MW - 1000MW$) presents the flexibility of exploiting biomass in via fluidized bed gasification in local small-scale plants based on the local resource. Yet, factors are affecting the reliability of locally available biomass such as weather conditions, agricultural practices, regulations, and competing uses for local biomass [78]. As a result, it requires critical assessment and forecasting of technically and financially available biomass quantities on an annual basis with a well-structured and proven methodology.

Densification techniques, such as baling, pelleting, briquet, and pyrolysis/torrefaction, help mitigate logistics costs associated with biomass transportation, storage, and handling, but the role of densification within the overall biomass-to-biofuel supply chain context is not yet well understood [89]. Densification by mechanical method increases the energy density of the biomass while torrefaction reduces the H/C and O/C ratio with the remaining 75–95% of total biomass energy

Property	Wood Pellets	Torrefied biomass Pellets	Coal (bituminous)
Moisture content (%)	7–10	1–5	5–10
Mass density (kg/m^3)	600–650	750–850	800–1000
LHV (MJ/kg)	16.2	19–22	> 25
CV (MWh/t)	4.5	5.2–6.2	7
Energy density (MWh/m^3)	3	4.2–5	5.6–7
Bulk density (GJ/m^3)	7.5–10.4	15–18.7	18.4–23.8
Nature	Hygroscopic	Hydrophobic	Hydrophobic
Grindability	Poor	Good	Good
Biological degradation	Yes	No	No

Adapted [6].

Table 4.
Comparison of properties of Wood Pellets, Torrefied Biomass Pellets, and Coal.

after removing moisture, hemicellulose, and partially cellulose [29]. CO and H_2 production apparently increases with torrefaction [26, 90]. It results in near-complete degradation of its hemicellulose content while maximizing the mass and energy yield of the solid product [91]. It increases the calorific value, energy density, grindability and makes the biomass more hydrophobic so that it can be more suitable for storage [92]. **Table 4** compares the characteristics of torrefied biomass against wood pellets and coal. Such feedstock upgrading techniques are getting increasing attention, yet have their associated investment and operational costs.

4.3 Lack of adequate policy frameworks and strategies

Policy and regulatory barriers can significantly hinder the deployment of biomass waste for decentralized heat and energy generation. For the case of Europe, although there are some at the national and industry levels, there are currently no legally binding sustainability criteria for biomass at the EU level [2]. Several countries offer varying incentives and frameworks for biomass utilization, thereby creating disparities in policies and regulations [93]. These barriers come in the form of legal, regulatory, institutional, and economic constraints. Government regulatory policies may lack clarity, and inconsistent or overly restrictive policies can impede progress in this field.

For instance, a lack of uniformity in the requirements for emissions monitoring can make it much more difficult and expensive for project developers to advance [94]. Additionally, unclear feedstock requirements can make it challenging for suppliers to comply, which could prevent the facility from operating at full capacity or necessitate significant changes in the facility's design. Furthermore, it is less profitable than fossil-based power due to the lack of financial incentives and subsidies for decentralized heat and energy production facilities. Another significant obstacle is the unequal playing field between renewable and non-renewable energy sources. Potential investors may be deterred from investing as a result of these regulatory restrictions that may make it more difficult to implement decentralized heat and energy generation facilities using biomass wastes.

In conclusion, there is a need for supportive policies and clear regulatory frameworks to encourage the deployment of decentralized heat and energy generation facilities that use biomass waste.

5. Techno economics

The ability of fluidized bed gasification technology to effectively transform a variety of feedstocks into a clean and renewable form of energy makes it a desirable option for distributed heat and power generation. To determine a biomass conversion plant's economic viability, techno-economic considerations must be taken into account. In addition to end product application and feedstock availability, challenges such as cost-competitiveness and sustainability constrain bioenergy development [95]. The cost of fluidized bed gasification varies depending on factors like the region of the world, the type of feedstock, the cost of supplies for conversion processes, the size of the production, and the length of the production process.

Numerous academic institutions and international organizations recognize biomass as one of the most cost-effective renewable energy sources for power production [3]. Various biomass power technologies are mature and have production costs that are competitive with electricity generation rates in the OECD, particularly with low-cost agricultural or forestry waste sources like wood pellets, according to a recent report by the International Renewable Energy Agency (IRENA) [96]. Due to their low capital and operating expenses, small-scale gasification technologies have been shown to be both technically and economically viable for the production of heat. Industries that need process heat and have access to biomass resources should use these systems [3]. Additionally, by combining electrification with readily available biomass fuels from the local area, small-scale gasification systems have the potential to promote rural development [3].

Diego et al. [3], stated that the levelized cost of commercial bioenergy for electricity or combined heat and power ranges from US $cents_{2005}$ 3.5 to $25/kWh$ (USD_{2005} $10to50/GJ$) for liquid and gaseous biofuels and roughly USD_{2005} 2 to $48/GJ$ for electricity or combined heat and power (CHP) systems larger than about $2MW$. The estimated price for domestic or district heating systems is between USD_{2005} 2 and $77/GJ$, with feedstock costs between USD_{2005} 0 and $20/GJ$ [3]. Appropriate gasifier systems with internal combustion engines can produce $1kWh$ of electricity from $1.1 - 1.5kg$ wood, $0.7 - 1.3kg$ charcoal, or $1.8 - 3.6kg$ rice husks [3].

A Cost Benefit Analysis framework can be used to evaluate the feasibility of fluidized bed gasification projects from an economic perspective. This framework aids in the technical and economic analysis of the bioprocess's domain data, including capital and operational costs, simulation, equipment installation costs, and project profitability [97, 98]. Truong et al. [99], studied the effect of plant size on the total capital investment (TCI), total production cost (TPC), and specific capital cost for a fluidized bed gasification plant with a gas engine, gas turbine, and combined gas and steam turbines. TCI and TPC increase linearly between $10 - 140\$M$ and between $1 - 12.5\$M/year$, respectively for plant size from 10 to $550t/d$. The gasification system with a gas engine has the lowest TCP while the gasification system with gas and steam turbines has the highest TCP, with a narrow difference between them. The SCC on the contrary, has a very steep decline in plant size between 10 and 50t/d, a medium decline between 50 and 150t/d, a slight decline between 150 and 300t/d, and almost no change beyond 300t/d. Also, the plant with steam and gas turbines has the least SCC ($/(kWh/yr)).

State-of-the-art tools like Aspen Plus can be utilized to make TEA based on thermodynamic modeling, and energy and/or exergy analysis. In simulating and optimizing the biorefinery process flow, the size of the equipment and utilities can be calculated. Based on variables like equipment cost and material, raw material and utility costs, operating time, and product yield, the operational cost and investment are quantified. The discounted cash flow (DCF) method additionally aids in evaluating the project's profits, excises, internal rate of return (IRR), net present value (NPV), remuneration period, and lowest selling price [88]. It is also important to take into account the financial incentives if applicable. Antonio et al. [11] showed that the NPV is about four times when the financial incentives are considered in the techno-economic analysis of a fluid bed gasifier and combined gas-steam cycle.

In order to account for uncertainties in the TEA of biorefineries and to take into account societal sustainability factors like employment, the Monte Carlo simulation can also be used. Financial metrics like revenue, lowest selling price, and profitability—which are frequently expressed are typically used to deliver the TEA's results [88]. **Table 5** summarizes some of the TEA conducted on fluidized bed biomass gasification plants.

6. Future prospects

With the increasing global focus on climate change abatement and transition towards renewable energy sources, biomass gasification via fluidized bed gasification provides an opportunity to reduce greenhouse gas emissions while generating energy. Several research studies have outlined the future prospects of fluidized bed gasification technology.

According to the IPCC 2012 special report [1], advanced biomass integrated gasification combined-cycle (IGCC) power plants are among the technologies that are at a pre-commercial stage. With higher biomass to the power conversion efficiency of about 35–40%, the IGCC is a very competitive and attractive technology compared to conventional ones, especially in small-scale decentralized heat and power plants. For countries with existing huge small-scale decentralized plants, converting the conventional technology with a relatively small modification is considered a huge opportunity. Jesper et al. [102] showed the prospects of decentralized heat and power generation via gasification in the Case of Denmark where there are many existing small-scale heat and power plants with versatile technological options including FICFB (fast Internally Circulating Fluidized Bed) and LT-CFB (Low temperature circulating fluidized bed). The FICFB is designed for the cogeneration of electricity and bio-SNG and the LT-CFB is designed for the cogeneration of power, heat, and bio-fertilizer, with overall estimated efficiencies of 97 and 90% respectively.

The future prospect of fluidized bed gasification lies in leveraging key instruments such as advances in research and development, following proven methodologies in techno-economic feasibility and sustainability, and standardized and consistent policies and strategies at the regional, national, and global levels as depicted in **Figure 4**.

Gasification plant	Techno-economic analysis	Refs
Forest biomass blends gasification for small-scale power production facilities (1000KW Units) in the Azores (Portugal)—validated against 250$kWth$ quasi-industrial biomass gasifier in a pilot-scale fluidized bed reactor	• NPV: 486k€2020 • IRR: 17.44% • PBP: 7.4*years*	[100]
Fluidized bed gasification-based polygeneration from SCB (sugar cane bagasse) in Brazil—annual operating hours 8000—representative biomass price 25€/t biomass	• PBP: 5.4 (DFB) and 7.6 (CFB) years • Plant operating time: 20 years • TCI: k€ (309, 427 & 398, 712 for BFB and CFB respectively) • SNPC: k€$_{2009}$/kWh (0.09 & 0.12 for BFB and CFB respectively)	[101]
Fluidized bed gasification of wood chips with gas engine—various capacities: 15, 50, 150, 300, 500t/d	• TCI $$M$: 11.5, 27.4, 44.9, 78.8, 127.3 with respect to capacities • SCC, \$/(kWh/yr)): 1.9, 1.3, 0.7, 0.6, 0.6 with respect to capacities • ASR M\$/yr: 1.3, 4.2, 12.7, 25.3, 42.3 with respect to capacities • PBP, yr.: –, 11.9, 5.4, 4.5, 4.3 with respect to capacities • ROI, %: –, 2.3, 11.0, 14.1, 15.2 with respect to capacities • DCFROR, %: –, 4.2, 15.4, 18.8, 19.9 with respect to capacities	[99]
Fluidized bed gasification of wood chips with gas turbine—various capacities: 15, 50, 150, 300, 500t/d	• TCI $$M$: 18.4, 30.1, 49.6, 78.7, 124.2 with respect to capacities • SCC, \$/(kWh/yr): 4.7, 1.9, 0.9, 0.6, 0.6 with respect to capacities • ASR, M\$/yr: 1.0, 3.7, 12.1, 25.5, 43.9 with respect to capacities—PBP, yr: –, 19.1, 6.7, 4.7, 4.1 with respect to capacities • ROI, %: –, −0.4, 8.0, 13.6, 16.1 with respect to capacities • DCFROR, %: –, −1.0, 11.9, 18.2, 20.8 with respect to capacities	[99]
Fluidized bed gasification of wood chips with gas and steam turbines—Various capacities: 15, 50, 150, 300, 500t/d	• TCI $$M$: 22.2, 34.1, 58.4, 94.6, 143.5 with respect to capacities • SCC, \$/(kWh/yr): 3.7, 1.3, 0.6, 0.5, 0.4 with respect to capacities • ASR, M\$/yr: 1.2, 4.7, 15.5, 32.8, 57.0 with respect to capacities—PBP, yr: -, 18.3, 5.8, 4.1, 3.5 with respect to capacities • ROI, %: -, −0.2, 10.0, 16.3, 20.0 with respect to capacities • DCFROR, %: -, −0.5, 14.3, 21.0, 24.8 with respect to capacities	[99]

DFB, Dual Fluidized Bed; CFB, Circulating Fluidized Bed; NPV, Net Present Value; IRR, Internal Rate of Return; PBP, Pay Back Period; TCI, Total Investment Cost; SNPC, Specific Net Production Cost; SCC, Specific Capital Cost; ASR, Annual Sale Revenue; ROI, Return on Investment; DCFROR, Discount Cash Flow Rate of Return.

Table 5.
Techno economic analysis conducted on different gasification plant designs.

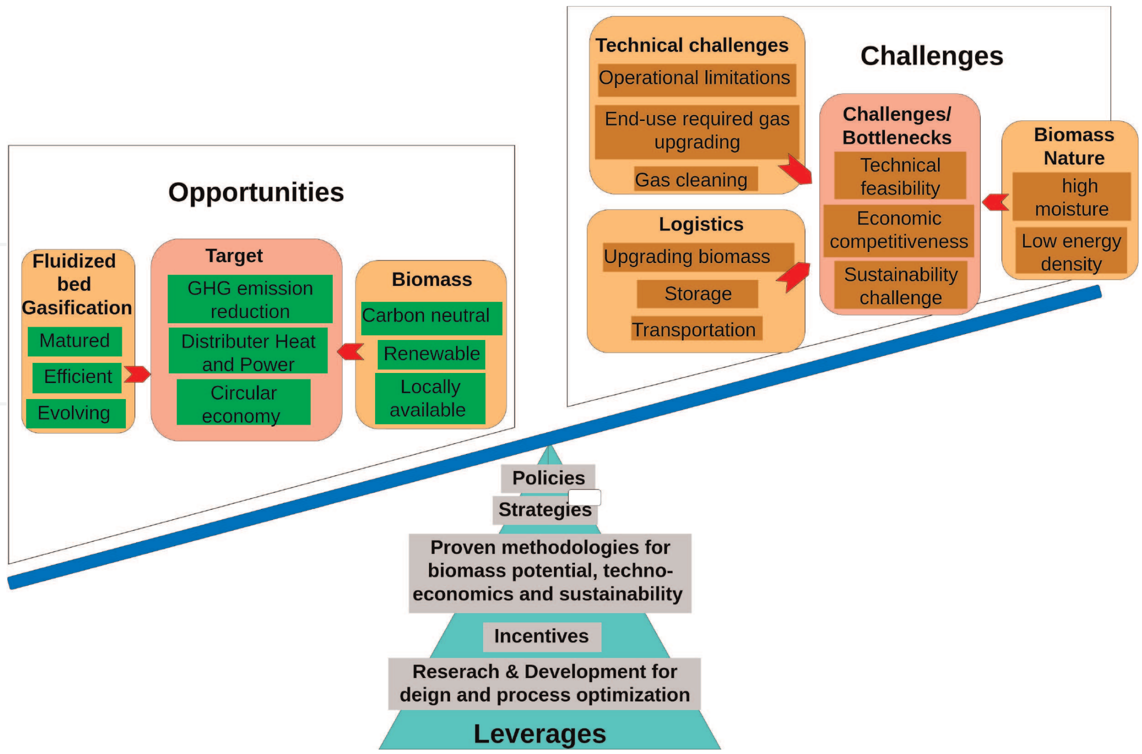

Figure 4.
Leveraging comprehensive instruments for opportunities outweigh challenges.

7. Conclusion

In conclusion, this study has demonstrated the significant promise of fluidized bed gasification technology in converting biomass wastes into viable energy sources for distributed heat and power production, thereby contributing to climate change mitigation efforts. By effectively harnessing waste materials, this technology offers a compelling means of reducing greenhouse gas emissions.

However, the widespread adoption of fluidized bed gasification necessitates the resolution of various challenges related to technology, supply chains, and policies. The optimization of the gasification process, targeting enhanced system performance, gas yield, and quality, emerges as a primary technical challenge. Additionally, managing the heterogeneity of feedstock compositions and developing efficient approaches for treating byproducts like tar and particulates pose substantial technical and economic obstacles.

Nonetheless, the overall conversion of biomass waste into energy through fluidized bed gasification presents a promising avenue for climate change mitigation, sustainable energy provision, and the promotion of circular economy principles. To fully capitalize on the benefits of this technology, it is imperative to establish well-defined policies. These policies should be designed to promote renewable energy sources and facilitate the widespread adoption of fluidized bed gasification technology.

By effectively optimizing the implementation of fluidized bed gasification in biomass-to-heat and energy conversion pathways, significant contributions can be made towards sustainable energy provision and addressing the pressing issue of climate change. Future research and development efforts should continue to focus on overcoming technical challenges, refining supply chains, and formulating comprehensive policies to unlock the full potential of fluidized bed gasification in biomass waste utilization.

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Conflict of interest

The authors declare no conflict of interest.

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