Promoting Sustainability through Single Fuel Mode Gasifier-engine Systems: A Framework for Cleaner Energy Solutions

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Promoting Sustainability through Single Fuel Mode Gasifier-engine Systems: A Framework for Cleaner Energy Solutions

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Abstract: Energy is of utmost importance in the United Nations' sustainable development goals, since it aids in promoting economic growth and societal progress. The disparity between the supply and demand of energy necessitates the substitution of fossil fuels with renewable fuel technology. Gasification is in line with the United Nations' objectives of providing accessible and environmentally friendly energy. It provides a solution for effectively managing trash in rural areas and enables small-scale power generation using engines operating in single-fuel mode (SFM). Companies are investing in improving engine performance by utilizing low-calorific-value producer petrol in SFM to support sustainable rural lives. This paper analyses the operational factors that might enhance the quality of producer gas generated from different types of biomass gasifiers. Additionally, it investigates the utilization of various gas mixes for engines equipped with spark-ignition, fuel-injected, and compression-ignition systems. The proposal recommends implementing a hybrid system for the management of rural garbage, which would also generate electricity. The study discovered that steam gasification improves the composition of producer gas, but the low laminar flame speed of biogas can be attributed to its high level of CO_2. By combining these gases, their drawbacks are eliminated, becoming them suitable for generating tiny amounts of power in rural regions. A hybrid plant that integrates biomass gasifiers and anaerobic digesters can effectively handle both solid and liquid waste while simultaneously generating a combustible gas mixture for power generation.

Keywords: Biomass gasification system; gasifier-engine system; single fuel mode; sustainable rural development; alternative fuel

1. Introduction

Over the globe, conventional fuels (i.e., derived from buried fossils) are the major sources of energy and power. Undesirably, these sources are getting depleted very rapidly due to their exponential exploitation, especially by the more affluent society; consequently, their utilization has been degrading the global environment very seriously[1-2]. To overcome such alarming issues, it is vital to discontinue the conversion model of development based on fossil fuels and further needs to conceive renewable energy sources such as bioenergy from bio-residues, solar energy, wind energy, etc[3-4]. Energy can also be harvested from the wind flow through smart materials[5-7]. Out of them, the bio-residues and solar energy are the most promising renewable source of energy, but the problems associated with the solar thermal power system like poor operating hours and fluctuation of energy supply are the key barrier for its popularity[8,9]. But the features offered by biomass, like easily availability in abundance in tropical countries, make it a more promising renewable source of energy as compared to solar energy[10,11]. It is renewable and can be utilized for the replacement of fossil fuel via the gas engine or gas turbine. This biomass energy can be transformed into modern energy carriers, such as producer gas (via thermochemical conversion) and/or biogas (via bio-methanation) through gasification, which is the approved, attractive, cost-effective, and environmentally benign choice of energy and power production[12]. These modern energy carriers derived from bio-residues can be substituted in gas-engine for motive power and electricity generation applications by coupling with a matched alternator. The biomass materials which are rich in lignin components along with low moisture contents are convenient for thermochemical conversion, whereas the biomass materials rich in cellulosic components with high moisture content (e.g., bovine wastes, organic wastes such as cow dung) are convenient for bio-methanation[13]. Such a combination of either a downdraft gasifier or biogas plant with a gas-engine in single fuel mode with a matched alternate is completely independent of fossil gasoline and the best choice to serve the rural or far-flung societies for decentralized electric power supply without any environmental degradation[14,15]. In present scenario, the decentralized power production systems at low power range and which are fully independent from fossil fuel are getting more demanding and attractive as an alternative gaseous fuel. These fuels can fulfill the UN sustainable development goals as shown in Fig. 1.

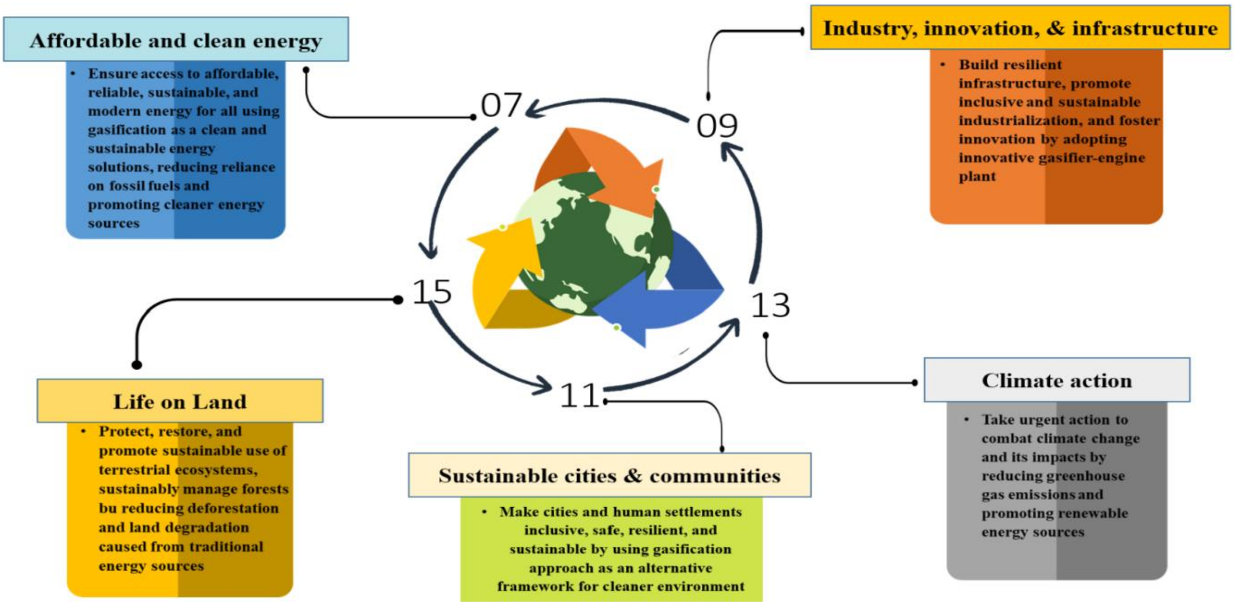

Fig. 1: An overview of UN sustainable development goal addressed in the present study for a prosperous livelihood and spur economic growth.

The waste, either solid or liquid waste, can be managed through biomass gasifier and anaerobic digester. These two systems can be utilized to produce gaseous fuel of different composition. The gas generated from biomass gasifier is known as producer gas which consists of different composition of various gases such as carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2), and methane (CH_4). Whereas gas from anaerobic digester is mixture of methane (CH_4) and carbon dioxide (CO_2). The main problem in utilizing the producer gas through engines is its low calorific value and this can be enhanced by mixing these two gases from the biomass gasifier and anaerobic digester. The primary objective of this study is as follow.

- Conditions of operating parameters to enrich the quality of producer gas through various biomass gasifiers using solid biomass waste.
- To identify the various gas mixtures of combustible gases such as (hydrogen, methane, and carbon monoxide) which can be utilized in engine in single fuel mode.
- To propose a hybrid system to manage rural waste (solid biomass through gasifier or liquid waste through anaerobic digester) and power production through engines in single fuel mode.

This review, therefore, focus has been made to review the contemporary research pertinent to the production of alternate gaseous fuels derived from gasification by the thermochemical conversion route and anaerobic digestion route. A proper mixture of various combustible gases from biomass gasifier and anaerobic digester may be a good alternative fuel for rural economic development from an environmental, financial, and energy perspective.

2. Biomass gasification

Syn gas, or producer gas, is produced by gasifying coal, biomass, or waste matter in an environment at a high temperature. Under controlled operating conditions and an oxygen deficiency, the feedstock partially oxidizes to yield producer gas[16]. Inside a gasifier, a series of reactions take place to produce gas. The processes and sequence of gasifier with respective reactions are shown in Fig. 2. In drying process, the feedstock is exposed to temperature above 100^0C to vaporize the moisture from biomass feedstock. Further, this dry material is exposed to temperatures above 240 ^{0}C called a pyrolysis process which leads to decomposing into char and volatile matters (i.e., tar or heavy hydrocarbons)[17]. Under the influence of a controlled amount of oxidizing agent, pyrolysis products migrate into the oxidation zone, often designated as the oxidation stage. In this phase, fundamental chemical reactions occur where the residual solid carbonaceous material (char) and volatile organic compounds, including tar, undergo oxidative degradation. The char predominantly reacts through heterogeneous oxidation processes, where oxygen molecules interact with the solid carbon surfaces, leading to the formation of CO and CO_2. Concurrently, the volatiles, which are complex mixtures of hydrocarbons, participate in homogeneous oxidation reactions in the gas phase, resulting in the formation of smaller molecules, such as CO, CO_2, H_2O, and various other oxidized species. This is important because if tars were to condense and form sticky substances, they may potentially harm the engine valves. The limitation regarding tar concentration in producer gas as an engine fuel is shown in Table 1. After that, these mixture goes under reduction process where remaining char reacts with carbon dioxide and water vapour components in product gas under the complete absence of oxidants. The raw producer gas exits the gasifier at high temperatures, containing impurities such as particulate matter, tar, and water vapor. It must be cooled to ambient temperature and purified to acceptable levels. Essentially, producer gas is a mixture of combustible gases (CH_4, H_2, CO) and non-combustible components (CO_2, water vapor, N_2), formed through a series of distinct processes. Hasler & Nussbaumer (1999)[18] and Bhatacharya et al. (2001)[19] carried out estimation for gas cleaning using conventional downdraft gasifiers, and standard required quality of gas for gas-engine and gas-turbine applications are listed in Table 1.

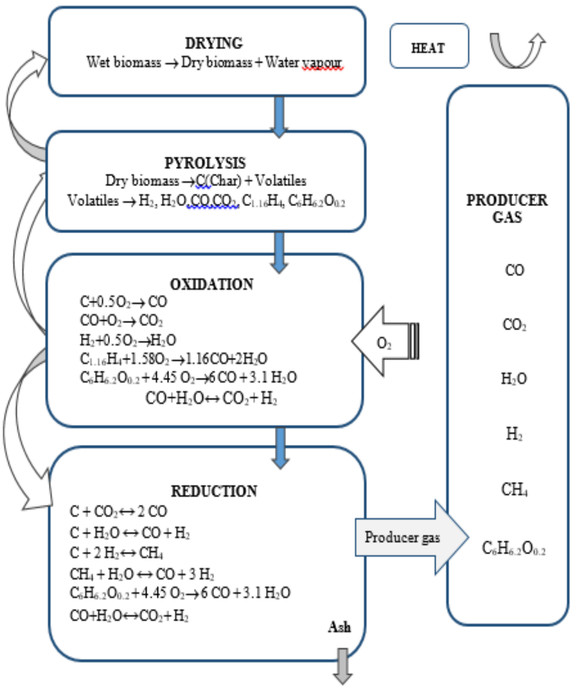

Fig. 2: Biomass gasification stages, heat, and material interactions.

Table 1. Producer gas/Biogas quality requirement for power generation via gas-engine/gas-turbine.

Particulars	**Gas-engine**[18]	**Gas-engine**[19]	**Gas-turbine**[18]
Particles (mg/Nm^3)	<50	-	<30
Particle Size (μm)	<10	-	<5
Alkali metal (mg/Nm^3)	-	-	<0.24
Tar (mg/Nm^3)	<100	1-10	-

For engine applications, the raw producer gas must be cleaned and cooled. This is achieved using various devices such as air-cooled heat exchangers, counter-current spray water chambers, direct water-contact cascaded flow systems, indirect contact heat exchangers, spray-cooling towers, cyclones, scrubbers, and filters. The direct-contact water spray towers are quite compact[20]. A cyclone is utilized to separate coarse particles or dust without any moving parts. The gas cyclones are the preliminary stage of gas cleaning; they separate only coarse particles of size less than 2μm. Electrostatic precipitators are highly reliable and remove up to 99.8% of particulate matter[21]. However, these types of equipment consume substantial electrical power. Significant progress has been made in improving the cooling cleaning system for gas generated from the gasifier[22,23]. The gasifier is linked to a hot gas conditioning system equipped with a commercial catalyst that effectively decreases the tar content in the raw producer gas. The chemical composition of various gaseous fuel is represented in Table 2.

2.1 Fixed bed gasifiers

Fixed bed gasifiers use feedstock in one or two stages to gasify coal or biomass. Downdraft gasifiers have opposite fluid flows, higher temperatures, and lower efficiencies[24,25]. Updraft gasifiers use the same path and lower temperatures, directing syngas upward with tars[26]. These fixed bed gasifiers are shown in Fig. 3. The chemical composition or calorific value of producer gas depends on biomass materials, density, particle size, moisture and ash content, flow configuration and gasifier design, and the catalyst[27,28]. The fixed bed gasifiers include a granular/porous bed in which the solid particles are gasified by gasifying agents for instance air, oxygen, and steam travel either in upwards or downwards direction depending on the type of design configuration[29].

Table 2. Typical chemical composition of various gaseous fuel.

Constituents (%Vol)	**Producer gas from wood**[30]	**Producer gas from charcoal**[30]	**Biogas**[31]
CO	20.0	23.0	-
CO_2	12.5	7.0	25-50(%)
H_2	19.5	14.0	0-1(%)
CH_4	2.0	<0.9	50-75(%)
N_2	46.0	55.1	0-10(%)
H_2S	-	-	0-3(%)

These configurations are the most basic type of gasification systems which consist primarily of the well-insulated cylindrical vessel holding biomass feedstocks and gasifying chemicals, a fuel feeding device, an ash collecting unit, and a gas outlet. These types of gasifiers are designed to work at modest pressures of 25-30 atm[32,33]. The performance of different types of gasifiers is summarized in Table 3.

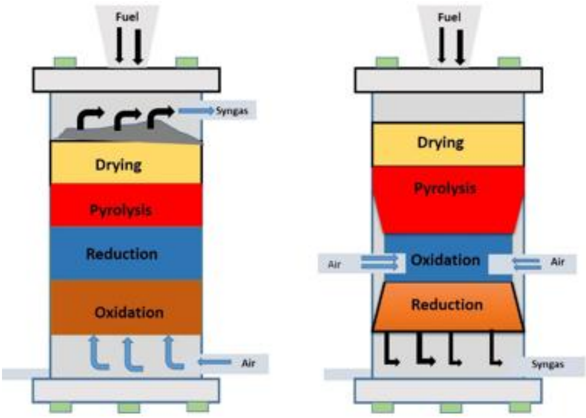

Fig. 3: Fixed bed gasifier (a) Updraft configuration (b) Downdraft configuration.

Table 3. Influence of Performance Parameters of gasification systems on quality of producer gas.

Researchers	Biomass type	Type of gasifier	Parameters evaluated	Findings	Significant advancements
Sharma[33)]	Kikar wood or Acacia Nilotica	Downdraft gasifier	Pressure drop, gasification efficiency, producer gas composition	Higher reaction temperature enhanced the gas quality during maximum pressure drop for the ignited gasifier.	Shows how the gasifier's performance is affected by the pressure drop across different auxiliary units.
Varanak et al. (2022)[34)]	Waste tires and sludge	Updraft fixed bed steel reactor	Optimization of composition of the producer gas	The response surface approach was used to determine the optimized producer gas composition.	BBD design was implemented to optimize the gasification parameters
Rabea et al. (2021)[35)]	Cotton Stalks	Downdraft gasifier	ER, syngas yield, heating value, gasification, and carbon conversion efficiency.	The optimum ER and airflow rates are 0.235 and 125 L/min, respectively.	Channeling problem occurred in operation of gasifier was resolved by altering the design of reactor.
Awais et al. (2021)[36)]	Sugarcane bagasse & coconut shells	Downdraft gasifier	syngas yield, ER, heating value, gasification efficiencies, and tar content.	Coconut shell biomass yields more syngas as compared to sugarcane bagasse. ER of 0.29 and 0.22 for coconut shell and sugarcane bagasse was recommended.	Find out whether sugarcane bagasse may be used in downdraft gasifiers as a biomass feedstock.
Bhoi et al. (2018)[37)]	Switchgrass & Redecedar	Downdraft gasifier	syngas yield, ER, heating value, gasification efficiencies, and tar content.	H_2 and CO composition, heating value, and syngas yield increased with ER. Tar content is reduced and lower in the case of Redcedar.	The performance of the gasifier was enhanced as it was scaled up from its laboratory size counterpart.
Omar et al. (2018)[38)]	Corn cobs & waste wood	Downdraft gasifier	biomass moisture content, ER, gasification agent, producer gas composition	5% moisture content in biomass with uniform air gasification enhances producer gas quality.	The tar content in the desired gas may be reduced by raising the reactor temperature in the oxidation and reduction zones.

Ma et al. (2015)[39]	Rice husk	Downdraft gasifier	ER, tar content, and composition distribution of producer gas	Rice husk char can be a feedstock for gasification. An optimum ER of 0.211 is reported for minimum tar and maximum efficiency.	Tar content present in the producer gas can be utilized in other application such as aromatic chemicals.
Simone et al. (2012)[40]	Wood sawdust pellet & pelletized meal	Downdraft gasifier	Pressure drop and composition of producer gas	Pelletized biomass is not ideal for gasifiers due to significant pressure drop.	Palletized biomass can be utilized in co-gasification process with different types of biomass feedstocks.
Pandey et al (2022)[41]	Biomass pallets of cylindrical shape	Imbert downdraft Gasifier	Composition of producer gas	Increment in concentration of CO from 23.96 to 31.37% in producer gas was reported.	Air was gasified with a mixture of CO_2 gas (0–45%).
Manu et al (2023)[42]	rice husk (RH), cashew shell, and cashew husk and their blends	Fluidized Bed Gasifier	CGE (%), producer gas yield, thermal efficiency, and carbon conversion efficiency (%)	Increment in all parameters values when ER was increased. 91% of CCE was observed when blending of rice husk and cashew husk was utilized in fluidized bed gasifier.	Blending of different biomass feedstocks results in enhancing the concentration of H_2 in desired gas

2.2 Fluidized bed gasifier

These type of gasifiers are an advanced gasification system where induced air or oxidant at the reactor's base suspends particles, causing the solid-gas mixture to behave like a fluid[43,44]. Such fluid-like behavior exhibits few uncommon characteristics, namely good mixing and better particle-to-gas contact enforcing tar cracking followed by improved thermochemical conversion efficiency. Among the two broad classes of fluidization bed namely, bubbling fluidized bed gasifiers (BFBG) and circulating fluidized bed gasifiers (CFBG), the former is used more commonly for big-scale applications because of its broad fuel flexibility, however, short residence time and tar laden product gas followed by producer gas having low calorific value are observed some limitations. In such gasifiers, silica is widely recognized as the most valuable inert bed material, along with other bulk materials that possess catalytic characteristics (i.e., olivine, glass beads, sand, and dolomite) are also being employed recently to suppress tar contents. Sui et al. (2020)[45] investigated the role of catalyst cracking (i.e., calcinated cement) to minimize the tar for air-steam fluidized bed gasification using pine sawdust/wood chips. They achieved the highest hydrogen concentration of 50.3 % while a minimum tar level of 0.49 g/Nm^3. The variation of composition of producer gas from bubbling fluidized bed gasifier with using catalyst and without catalyst is compared in Table 4.

Table 4. Performance comparison of fluidized bed gasifier (air medium) from literature pine wood pellets, BFBG.

Particulars	**Pio et al. (2018)[46]**	
With/without catalytic	Without	With
CO (%)	7.7-16.9	14.2-37.6
H_2 (%)	3.2-8.3	9.5-14.7
CH_4 (%)	0.5-4.4	2.6-3.5
CO_2(%)	9.5-14.6	3.6-14.8
LHV(MJ/Nm^3)	2.4-4.3	3.9-6.3
Carbon conversion efficiency (%)	30.7-50.9	56.8-86.6
Cold Gas efficiency (%)	13.7-30.5	38.1-66.3

The Toroidal or Swirling Fluidization Bed Gasifier (TFBG) represents an innovative advancement designed to address certain limitations of traditional gasifiers. By mitigating the axial momentum of particles and instead channeling a substantial portion of the momentum radially and tangentially, the TFBG promotes enhanced mixing and exhibits more fluid-like behavior, while simultaneously reducing particle elutriation[47,48]. Barath et al. (2018)[49] designed a bubbling fluidized bed gasifier (BFBG) that has a thermal output of 40 kWth. Their research focused on the co-gasification of rice husk and coal in different ratios, uncovering notable results when combining ash coal and rice husk in proportions ranging from 50% to 75%. Table 5 provides a summary of the performance of several fluidized bed gasifier designs, as documented in the literature, for the purpose of comparison.

Table 5. Performance comparison of fluidized bed gasifier (air medium) from literature.

Particulars	**Kim et al. (2013)**[47]	**Bharath et al. (2018)**[49]	**Sharma et al. (2022)**[48]
Design	BFBG	BFBG	TFBG
Fuel	Wood pellet	Rice husk (90%) + Sawdust (10%)	Sawdust
CO (%)	11.8-16.1	14.0	14.9-16.0
H_2 (%)	14.5-16.5	8.64	15.3-16.3
CH_4 (%)	4.7-5.3	5.63	2.3-3.5
H_2/CO	1.0	~0.64	~1
CO/CO_2	0.69 - 0.98	1.13	1.04 - 1.18
Temperature (K)	1023-1073	1065	1015-1036
LHV(MJ/Nm^3)	5.3	4.84	4.7-5.5
Gasification efficiency (%)	72.2%	63.36 %	66.7-74%

3. INDUCTION SYSTEM

A gas carburetor or induction system is essential for regulating the air and fuel mixture in the charge and enabling the integration of the gasifier with a gas engine system. Several innovative designs of gas carburetors or induction systems have been reported. Sridhar[50] developed a gas carburetor based on zero-pressure regulator concepts, which maintains ambient gas pressure to control the air-fuel ratio for a gas engine. This design ensures accurate fuel delivery but exhibits a sluggish response and hysteresis under sudden load changes. Sridhar's research also exposed the misconception that producer gas engines must operate in single-fuel mode at high compression ratios, demonstrating smooth operation without knocking at compression ratios up to 17. This finding was significant in advancing the potential for higher efficiency in gas engines using producer gas. Banapurmath and Tewari[51] proposed a Y-shaped induction system specifically designed for dual-fuel gas engines. Their design facilitates efficient mixing of producer gas and air, optimizing combustion and performance in dual-fuel mode. Kumar and Sharma[52] designed a swirl gas carburetor using ANSYS software, incorporating advanced fluid dynamics to enhance the mixing of air and producer gas. Experimental observations concluded that the swirl gas carburetor operates smoothly across a wide load range, ensuring stable performance and efficient combustion. This design innovation contributes to improved engine performance and reduced emissions, highlighting the importance of precise air-fuel mixture control in gas engine systems. These advancements in gas carburetor and induction system designs are crucial for optimizing the performance of gas engines running on producer gas, making them more efficient and adaptable to different operational demands.

4. Producer gas as an alternative fuel to SI engines

Producer gas finds application in spark-ignited engines as a substitute for gasoline or natural gas, thereby enhancing the versatility of SI engine utilization[53]. The key advantages of the producer gas engines are the low operating cost and environmental impact compared to fossil fuel engines. These gas engines are not commercially available due to the variety in producer gas composition. So, it can be made by altering some arrangements in existing diesel or gasoline engines. This article primarily focuses on demonstrating various engine performances in single-fuel mode. In this domain, numerous studies have been reported on modifying or converting existing engines for producer gas in single-fuel mode. Attri et al. (2020)[54] transformed a conventional diesel engine into a cutting-edge producer gas-powered engine. They installed a battery ignition system, a contact breaker unit, and a spark plug. The compression ratio (CR) was also decreased by increasing the clearance volume of the piston. A gasoline carburetor was also installed to start the engine in gasoline mode to switch to producer gas mode. Shah et al. (2010)[55] studied the thermal efficiency and emissions characteristics of a producer gas engine. They found that CO and NOx emissions were low, whereas CO_2 emissions were comparatively high. Additionally, the overall efficiency of the gas engine remained consistent at maximum power output with both the syngas and gasoline models. Tsiakmakis et al. (2014)[56] examined the combustion performance of an SI gas engine (single-cylinder) coupled with a fluidized-bed gasification system for combined heat and power processes using three types of agriculture residues (i.e., peach, olive, and grape kennels). The blending of producer gas with propane was used at various engine speeds, and power de-rating with the range of 10% has been reported. Gobbato et al. (2015)[57] explored the capabilities of a robust natural gas engine, adapted to run on producer gas sourced from wood chips. The gas engine in producer gas mode was operated for over nine months without any unexpected maintenance. The engine's power output may undergo a reduction ranging from 30% to 70%, influenced by factors such as gas quality and engine compression ratio. Homdoung et al. (2015)[58] compared the theoretical and experimental performance of a spark-ignited producer gas engine at a compression ratio of 14 while spark timing was set at 30° BTDC. Babu et al. (2016)[59] analyzed the performance and combustion characteristics of a modified spark-ignited producer gas engine operating at a compression ratio of 11, utilizing a fixed composition of producer gas (bottled gas). Their findings highlighted a power derating of approximately 20.7% at rated load due to the lower heating value of the producer gas fuel, which was 32.3% lower compared to conventional fuels. Chunkaew et al. (2016)[60] performed experimental investigations on a converted HONDA make spark-ignited engine(model GX-120) for producer gas with compression ratio varied from 7.5 to 9.3 and air inlet valve opening of 30% and 75% and recommended higher compression ratio for more power especially with biomass gas

5. Biogas as an alternative fuel to an SI engines

Significant research has been dedicated to the production of biogas through anaerobic digesters. Biogas typically comprises methane and carbon dioxide, alongside impurities like moisture and H_2S[61]. Techniques such as moisture scrubbing with purifying agents like $CaCl_2$ and silica gel are employed to remove these impurities from raw biogas. Once purified, biogas is termed natural gas, which is widely utilized in internal combustion engines globally for power generation. This review focuses on literature pertaining to the use of biogas as a single fuel in gas engines. In their research, Huang & Crookes[62] investigated the dynamics of single-cylinder SI engines under various operational scenarios using simulated biogas. They found that the inclusion of CO_2 in the biogas resulted in reduced NOx emissions. However, this enhancement was accompanied by a decline in engine power and thermal efficiency. They recommended a higher compression ratio with biogas fuel with higher CO_2 presence in gas. Yadav et al.(2013)[63] studies and analyse by conducting an experimental investigation to reduce emissions from single-cylinder SI engines by using unpurified and purified biogas instead of gasoline. The compression ratio and relative air-fuel ratio were varied to observe SI engine performance. They reported that such engine conversion or modifications are useful for conversion efficiency and low emissions performance while operating on refined biogas fuel. Porpatham et al. (2018)[64] planned the experiments on a diesel engine (single-cylinder) modified as an SI engine (by lowering the compression ratio from 17:1 to 13:1) for operational biogas fuel. Oxygen concentration in the air was enriched in the range from 21% to 23%. They recommended high brake thermal efficiency and power output due to increased oxygen concentration. Further increase of oxygen concentration beyond 23%, NOx concentration shoots up. Sadik & Iyer[65] upgraded a compact 100 cc SI (motorcycle) engine to explore its performance using purified biogas containing 93.5% methane and raw biogas with 56.5% methane. They determined that selecting appropriate piston geometry and compression ratio adjustments could significantly improve the engine's operational efficiency. Hotta et al. (2018)[66] explored how varying the compression ratio affected a 4.4 kW water-cooled, single-cylinder spark ignited engine fueled by raw biogas (56.6% CH_4). They achieved a peak brake power output of 2.93 kW at 76.27% maximum load with a compression ratio of 15.29. Interestingly, they found that CO and HC emissions decreased at this compression ratio. However, there was an upward trend in NOx emissions as the compression ratio increased. Pandya et al. (2016)[67] compared the performance of converted engines operated on enriched biogas and petrol for the same compression ratio. Although the mechanical efficiency of SI engine for enriched biogas and petrol was 42.93% and 30.87%, respectively, enriched biogas is the best alternative gaseous fuel from a performance and economics perspective. Ji et al. (2013)[68] investigated how the addition of syngas, primarily composed of carbon monoxide and hydrogen, influenced the combustion and emissions performance of gasoline engines, particularly under lean conditions. They observed improvements in thermal efficiency alongside reductions in emissions following the introduction of syngas. Park et al. (2011)[69] studied the effect of variation in biogas composition on engine performance. A spark-ignited engine of Hero Honda bike was modified to be operated on biogas, and they concluded that modifications are required due to biogas fuel's slow fame propagation speed. In their study, Kim et al. (2016)[70] explored how different compositions of biogas, particularly varying ratios of CH_4 to CO_2, influenced engine performance. They highlighted that utilizing biogas with CO_2 under stoichiometric conditions showed promise for reducing NOx emissions. Likewise, Kwon et al. (2017)[71] explored the impact of compression ratio (8.01-9.22) and CO_2 dilution (0-50%) on the performance of small SI engines running on biogas. They found that increasing the compression ratio improved the engine's brake thermal efficiency significantly, boosting it from 22.0% to 29.9%. However, they noted that maximum engine performance was achieved at lower levels of CO_2 dilution. Jhalani & Sharma[72] investigated the performance parameters of a SI engine using raw biogas (presence of H_2S and moisture) and treated biogas. Thermal efficiency was reported higher when raw biogas was treated with $CaCl_2$ compared to silica gel. Exhaust emissions were observed lower with the use of treated biogas.

6. Producer gas enriched by bio-methane or hydrogen gas as an alternative fuel in SI engines

Cooled and cleaned biogas produced from either biomass gasification/ anaerobic digestion is utilized in modified internal combustion engines. Conventional fuels are fully eliminated. As biogas has different properties than conventional fuels, the existing requires some modification and performance of these engines to be optimized at all conditions. Numerous works have been reported on the performance prediction of gas-engine using enriched producer gas or biogas from hydrogen gas, methane and /or CNG. Kahraman et al. (2009)[73] presented investigations on a SI engine (Fordmake) at different fuel combinations with (i.e., 100% CH_4, 10% H_2 + 90% CH_4, 20% H_2 + 80% CH_4, and 30% H_2 + 70% CH_4) at 1500, 2000, 2500 and 3000 rpm at a compression ratio of 10.

They reported increased thermal efficiency with hydrogen addition to methane, while unburnt hydrocarbon and CO emissions were found in decreasing order. Further, CO fraction also decreases with engine speed and excessive air ratio. Porpatham et al. (2013)[74] investigated the effect of H_2 enriched biogas for using a gas engine with varying spark timing. They reported an increasing trend in thermal efficiency and power output with hydrogen addition up to optimum spark timing of 16° BTDC, while NOx emissions were in decreasing order. Arroyo et al. (2013)[75] investigated the spark ignition engine of Lamborghini. Results of gasoline, methane, and biogas mode were compared for synthetic gases derived from the catalytic decomposition of biogas. An increase in the emission of CO and CO_2 was reported, and the use of synthetic gases results in higher efficiencies compared to gasoline mode at high speed for a lean air-fuel mixture. Hydrogen gas fraction improves the combustion process, while a decrease in CO_2 emission was reported. Szwaja et al. (2013)[76] investigated gas-engine performance on syngas derived from municipal sewage sludge. Since syngas from sewage provides trouble operation, thus the gas enrichment from 40% CH_4 is recommended for smooth operation. Hagos et al. (2015)[77] presented experimental investigations to highlight the influence of CH_4 enrichment in syngas on the performance characteristics of direct injection spark-ignited engines. They found faster, smoother, and more efficient combustion with lower CO and hydrocarbon emissions, while NOx was relatively higher than syngas. Thus, there is a suitable option to replace the use of CNG. Verma et al. (2016)[78] explored the limitations of hydrogen enrichment in an engine without any major retrofications/ modifications without any considerable performance degradation. The relative air-fuel ratio was kept constant to avoid any possibility of a misfire. Chen et al. (2012)[79] studied the behavior of combustion of biogas blended with H_2 and CO in an SI engine. CO_2 is also added to predict the behavior of combustion. They set the thermal efficiency of 26% as an acceptable level. These blended fuels with biogas enhance the SI engine performance very well. Babu et al. (2018)[80] reported the effect of variations in the concentration of methane and hydrogen in producer gas on the in-cylinder combustion characteristics. Nine sets of producer gas were analyzed with different methane and hydrogen fractions. It was observed that hydrogen fractions could enhance combustion characteristics. Zhang & Hou[81] performed experimental investigations to explore the performance and emissions of gas-engine fueled with a mixture of CNG and hydrogen. An increase in indicated thermal efficiency of low calorific value gas was observed with H_2 gas addition, controlling hydrocarbon emission, while CO and NOx emissions are observed to be increased. Jeong et al. (2009)[82] extracted the emissions and efficiency of a spark-ignited gas engine operated on biogas blended with the hydrogen content (the content of the addition of hydrogen gas varied). The maximum generating (electric) efficiency of 29.26% was reported at an excess air ratio of 2 and 15 % hydrogen concentration. They concluded that hydrogen enrichment to biogas enhances engine performance, namely brake power output, generating (electric) efficiency, and maximum cylinder pressure. Park et al. (2011)[83] carried out an investigation of influence of EGR on an SI engine on performance and emission performance using hydrogen-blended biogas. Due to using EGR, the spark gap has to be modified to prevent a misfire. Thus, maximum performance was observed with a blending of 5-10% H_2 in biogas, while NOx emissions were observed to be decreased. They also conducted a numerical investigation to predict an SI engine's performance and emissions by varying the boost pressure. Kan et al. (2017)[84] investigated numerically and experimentally the utilization of syngas and biogas in a premixed SI engine. At maximum brake torque, indicated thermal efficiency of syngas and biogas-operated SI engines are 39.0% and 37.5%, respectively. Ignition timing plays an important role in the performance of an SI engine operated on syngas. It was observed that syngas and biogas blends could run premixed SI engines. There was no sign of any knocking during the operation. NOx emissions can also be reduced by using blends of these gaseous fuels. Zhang et al. (2017)[85] performed comprehensive experimental studies on heavy-duty SI engines operated on biogas from two-phase anaerobic digestion. Six models of biogas were used with different compositions. The addition of hydrogen to biogas enhances the combustion characteristics. Unfortunately, NOx emissions were increased upon the addition of hydrogen gas into biogas. Park & Choi[86] examined numerically the effect of hydrogen addition in biogas on the lean operating conditions of spark-ignited gas engines. They concluded that the addition of hydrogen and CO_2 content in biogas enhances the performance of a gas engine operated in spark-ignited mode. The effect of boost pressure was also observed in this analysis.

7. Results and discussions

The reviewed literature highlights diverse biomass sources suitable for biomass gasification to produce renewable alternative fuels. This study compares producer gases generated from various gasification methods and assesses their impact on engine performance. The influence of gasification agents on gas quality is also examined. Furthermore, the study investigates the enrichment of producer gas with hydrogen or biomethane for optimizing spark ignition engine operation in single fuel mode. It also discusses the limitations of enriching producer gas with hydrogen or biomethane.

7.1 Characteristics of producer gas

Various types of gasifiers have been extensively studied, including fixed bed and fluidized bed configurations. The quality of producer gas significantly hinges on operational parameters specific to each gasifier, such as biomass moisture content, equivalence ratio, gasifying agent, and reactor temperature. These parameters exert a profound influence on the composition of major combustible gases, particularly hydrogen (H_2) and carbon monoxide (CO), which are pivotal in determining the lower heating value (LHV) of the producer gas. Figure 4 and 5 illustrates the distinct compositions of H_2 and CO in producer gas from Imbert downdraft gasifiers (Fig. 4) and fluidized bed gasifiers (Fig. 5), showcasing how different biomass feedstocks yield varied gas compositions. Notably, the introduction of air steam as a gasifying agent in downdraft gasifiers has shown to enhance the composition of H_2 and CO, achieving percentages of 28.7% and 35.5%, respectively[87]. Conversely, catalysts like limestone, calcined dolomite, and olivine are employed in fluidized bed gasifiers to augment H_2 and CO composition, achieving levels of 49.1% and 27%, respectively[88]. The LHV of producer gas ranges significantly, from 10-28 MJ/Nm^3 when steam or oxygen is employed as the gasifying agent, to 4-7 MJ/Nm^3 when air is used. As the composition of these combustible gases increases, Figure 4 and 5 illustrates how the LHV of the gas mixture correspondingly rises, underscoring the critical role of gas composition in determining energy potential.

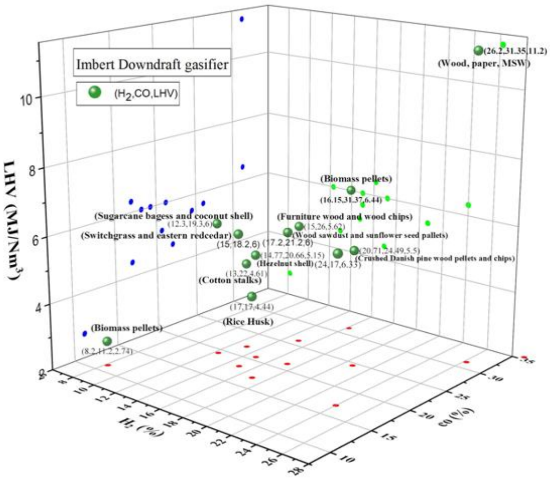

Fig. 4: H_2, CO, and LHV obtained from fixed bed gasifiers.

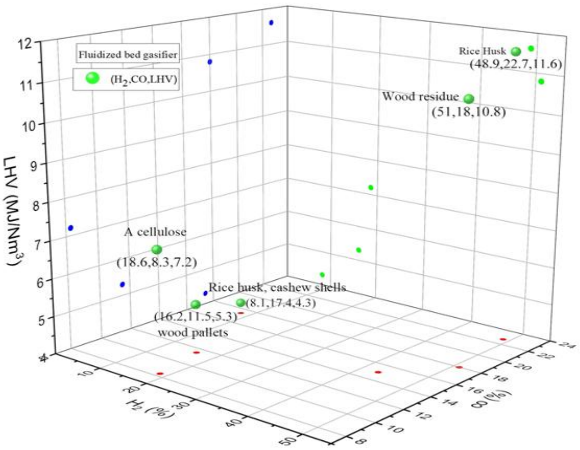

Fig. 5: (a) H_2, CO, and LHV obtained from (b) fluidized bed gasifiers.

The purified gas from these gasifiers is ideal for use in spark-ignited engines operating on a single fuel basis. Enhancing the quality of producer gas through steam gasification to increase hydrogen and carbon monoxide content presents a promising alternative fuel option for these engines. However, research on steam gasification and catalyst utilization in gasifiers is limited due to their complex operation and the high maintenance demands of the equipment.

7.2 Effect of utilizing producer gas as a fuel in single fuel mode

Due to the lower calorific value of producer gas compared to traditional fossil fuels like gasoline, spark-ignited engine performance is generally expected to be reduced. However, this decrease is less pronounced due to the producer gas-air mixture's lower air-to-fuel ratio under stoichiometric conditions. When operating near stoichiometric conditions, the energy density of syngas is comparable to that of conventional fossil fuels. Power derating in syngas fueling is influenced by both the decreased fuel heating value and reduced engine volumetric efficiency. Various types of gasifiers produce producer gas used in spark-ignited engines operating in single fuel mode. This study compares and discusses engine performance parameters such as optimized compression ratio, brake power, and maximum brake thermal efficiency. Figure 6 presents these parameters alongside the performance with different biomass feedstocks used to produce producer gas. The high laminar flame speed significantly impacts engine performance, influencing engine design and pollutant emissions based on mixture composition, pressure, and temperature. This parameter is often calculated using the H_2/CO ratio of the gas under consideration. The observed power de-rating when using producer gas as a single fuel in spark-ignited engines varies from 8% to 54%. The highest de-rating of 54.6% was noted when wood biomass was utilized in an updraft fixed bed gasifier[89]. Conversely, the maximum brake thermal efficiency reached 23.6%

when producer gas from a downdraft gasifier was employed. These findings underscore the complexities and trade-offs involved in optimizing engine performance with producer gas as a sustainable fuel source.

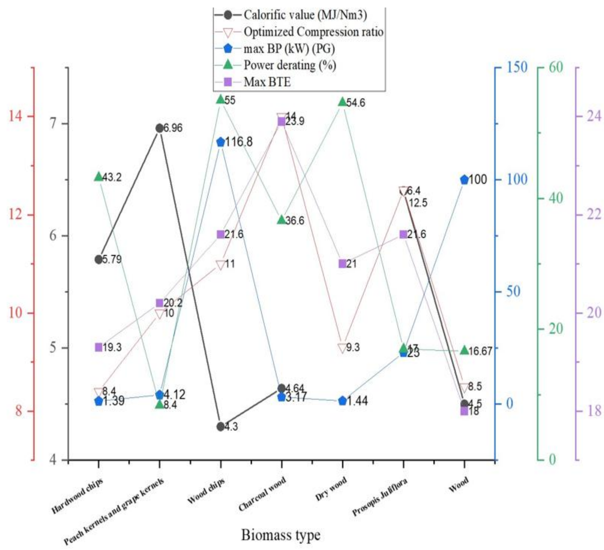

Fig. 6: SI engine performance using producer gas in single fuel mode.

To utilize producer gas as a fuel in carbureted and port-injection engines, test engines must undergo modifications. Thus, engine performance is compared to standard fossil fuels like diesel or gasoline. To determine the maximum compression ratio, investigations frequently establish knock operating conditions. However, researchers may reach different findings and outcomes. The explanation varies according to engine parameters, producer gas composition, feedstock properties, and gasifying agent. The literature study indicates efficient usage of this fuel under lean circumstances, resulting in minimal nitrogen oxide emissions and fuel consumption. This engine required for producer gas utilization should have generally high compression ratios to enhance performance. Although beneficial, the power output is lower than gasoline engines, and the trade-off between NOx and CO emissions and poor volumetric efficiency remain unsolved. There needs to be more focus for finding the better solution of this problem.

7.3 Effect of utilizing biogas as a fuel in single fuel mode

The composition of biogas is primarily influenced by the type of feedstock used and the operational conditions of the anaerobic digester. Adapting biogas for use in SI engines involves minimal adjustments, akin to gaseous fuels, with a focus on optimizing the delivery of the gas-air mixture rather than carburetion. Increasing the compression ratio (CR) in SI engines enhances thermodynamic efficiency, reduces brake specific gas consumption (BSGC), and increases power output while operating safely below the knocking threshold[90]. However, compared to gasoline, biogas typically exhibits a lower laminar flame speed, which can diminish volumetric efficiency in engines. Figure 6 illustrates the relationship between brake power and brake thermal efficiency with an optimized compression ratio. Figure 7 showcases the variation in methane (CH_4) composition within biogas, reflecting different operational conditions and feedstock types. Engines utilizing biogas with varying methane compositions in single fuel mode have been documented in the literature, employing compression ratios ranging from 9 to 15. The maximum observed brake thermal efficiency with optimized parameters fluctuates between 18% and 32%, highlighting the diverse performance outcomes achievable with biogas in SI engines. These findings underscore the multifaceted considerations in optimizing engine performance with biogas as a sustainable fuel source.

To utilize biogas as a fuel to spark ignited engines, conventional diesel engines can be modified to be operated on spark ignited mode because they offer high compression ratio. The laminar flame speed of biogas combustion in cylinder can be enhanced by adding hydrogen gas to it[91]. So, hydrogen can be enriched by mixing the producer gas with biogas. This can also eliminate the problems of solid and liquid waste from the rural areas.

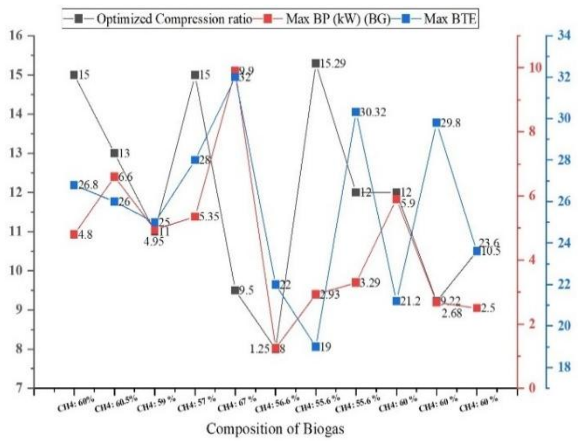

Fig. 7: SI engine performance in single fuel mode using biogas.

7.4 Effect of utilizing producer gas enriched by bio-methane or H_2 as a fuel in single fuel mode

As the individual study regarding the producer gas engines and biogas engines is vast. The calorific value of producer gas is low, which needs to be enhanced by adding biogas. This mixing exhibits a balanced composition of methane, carbon monoxide, and hydrogen which leads to optimized combustion efficiency. On the other hand, biogas from anaerobic digesters has lower methane concentration due to which laminar flame speed decreases. This can be enriched by the addition of hydrogen gas from producer gas. The combination of producer gas and biogas results in improved characteristics as compared to individual gases. The utilization of various mixtures of hydrogen gas and methane gas in spark ignited engines and performance of engines are compared and discussed. The relation between hydrogen and methane gas mixture in the desired gas with respect to optimized compression ratio and maximum brake thermal efficiency is shown in Fig. 8. Hydrogen (H_2) plays an important key role in flame propagation due to its high diffusivity, high flame speed, and low molecular weight[92].

As there is limitation of producer gas as well as biogas for utilizing these in SI engines in single fuel mode. These limitations can be eliminated by mixing these two gases for power production through spark ignited engines by a hybrid plant as shown in Fig. 9. This plant is very promising for rural waste management and small power production for rural development. The combustion properties of different mixtures of combustible gases from producer gas and biogas is presented in Table 6.

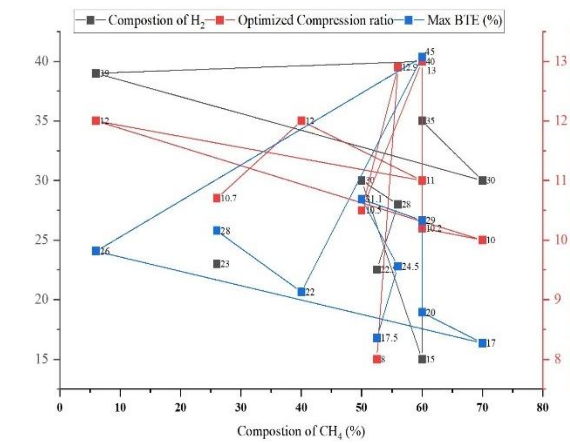

Fig. 8: SI engine performance in single fuel mode using producer gas enriched by biomethane or hydrogen gas.

Table 6. Properties of different mixture of combustible gases.

Properties	**Biogas**[93]	**Natural gas**[93]	**Syngas 1**[77]	**Syngas 2**[77]
Composition % vol.				
H_2	-	-	50	40
CO	0.18	-	50	40
CH_4	57	85	-	20
Laminar flame speed (cm/s)	25	34	180	-
Peak flame temperature	-	-	2385	2400
LHV (MJ/kg)	17	50	17.54	24.4
Density at 1atm and 15ºC	1.2	0.79	0.67	0.68
A: F ratio	5.8	17.3	4.58	7.23
Auto ignition temperature	650°C	540°C	873-923K	873-923K

8. Techno-economic and environmental aspects

8.1 Techno-economic aspects

Large-scale biomass gasification systems, with capacities exceeding 1 MW, are increasingly favored for power generation globally, especially in developed nations, owing to their lower initial investment costs and minimal impact on power distribution[94]. Shifting from fossil fuels to biomass in electricity generation has the potential to slash greenhouse gas emissions by 80% to 90%, as reported by the IPCC[95]. The techno-economic analysis of biomass gasification plants typically evaluates metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP)[96,97]. For instance, recent analyses have shown a calculated NPV of 2.367 MV, an IRR of 8.66%, and a PBP of 23.1 years, demonstrating the feasibility of such investments in rural areas of underdeveloped countries. It's noted that the viability of these projects heavily depends on governmental policy frameworks. Wang et al. (2019)[98] conducted a techno-economic analysis focusing on an entrained flow gasifier using wheat straw as feedstock, comparing biomass-to-hydrogen (BtH) and coal-to-hydrogen (CtH) processes. Their findings indicate that BtH was more cost-effective than CtH, particularly when considering tax implications. This underscores biomass gasification's position as a leading technology for sustainable power production.

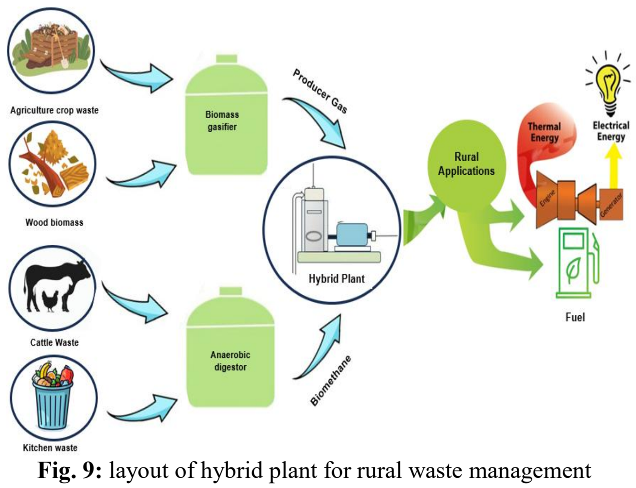

Fig. 9: layout of hybrid plant for rural waste management and power production.

8.2 Environment Aspects

In the context of rural economies, both anaerobic digestion and biomass gasification technologies have substantial environmental impacts. Through biomass gasification, wastes such as agriculture residues, wood, organic wastes can be utilized to produce green fuel and reduces the need for open burning and landfilling[99,100]. All such factors marking to the technology more useful and ambient benign. While in anaerobic digestion, methane rich biogas is produced which can be utilized for cooking, heating, and electricity generation. This assists in substituting conventional and often environmentally harmful energy sources in rural areas. The residual digestate from anaerobic digestion consists of nutrient rich fertilizer which can be used to enhance the soil fertility. This practice promotes sustainable agricultural methods and diminishes reliance on synthetic fertilizers. Figure 7 describes the research findings of the present study in context of hybrid plant operated on producer gas/biogas for its use in rural areas.

9. Conclusions

In the present study, contemporary research works on the production of renewable gaseous fuel via thermochemical conversion and anaerobic digestion are analyzed along with the critical issues related to the utilization of these gaseous fuels in internal combustion engines in single fuel mode. Studies were also conducted related to gas enrichment by hydrogen or bio-methane, existing engine conversion into gas-engine, gas composition variation and combustion quality in gas-engine, and engine power deration. This research proficiently examined the adoption of a single fuel mode hybrid gasifier-engine plant as an alternative framework for promoting a sustainable and cleaner environment using gasification as a viable solution to reduce greenhouse gas emissions. Gasification technology transforms diverse biomass feed-stocks into clean, renewable energy sources, offering a sustainable alternative to fossil fuels while mitigating their environmental footprint through combustion. Furthermore, the implementation of this alternative framework contributes to the goal of ensuring access to affordable, reliable, sustainable, and modern energy for all and rural communities can become self-sufficient in meeting their energy needs by utilizing locally available biomass resources. This not only improves energy security but also promotes economic development and poverty alleviation. Additionally, the adoption of a single fuel mode hybrid gasifier-engine plant aligns with sustainable development goal, which aims to combat climate change and its impacts. Through reducing greenhouse gas emissions and advancing renewable energy adoption, this framework actively combats the detrimental impacts of climate change, including intensified weather patterns and sea level rise. The successful adoption of a single fuel mode gasifier-engine plant requires not only the availability of appropriate technology but also the capacity building of local communities and stakeholders. However, further research and investment are necessary to overcome the challenges associated with technology adoption and ensure its successful implementation on a larger scale. Therefore, this study emphasizes the need for collaboration between governments, academia, and industry to facilitate the widespread adoption of this alternative framework.

10. Future scope

The combustion of these mixtures of combustible gaseous fuel in modified gas engines needs detailed research. A hybrid system may be a good alternative to manage rural waste. For utilizing solid wood waste, biomass gasifier can be installed and for liquid waste, anaerobic digester can be installed to produce mixture of gases. A detailed study of engine parameters utilizing these mixture of gases is required for design and development of engines in single fuel mode.

Declaration of interest

Authors firmly declare that they have no personal, financial or any other conflict of interest regarding this submission.

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