Hydrogen Rich Product Gas from Air–Steam Gasification of Indian Biomasses with Waste Engine Oil as Binder

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Abstract
Production of hydrogen rich product gas through thermochemical energy conversion having the biomass gasification is making significant inroads for green hydrogen fuel generation. In the present work, detailed physical and chemical characterization, air and air–steam biomass gasification of four biomasses i.e., Kasai Saw Dust, Lemon Grass, Wheat Straw and Pigeon Pea Seed Coat from four different group of biomass production system at different steam to biomass ratio, equivalence ratio and with and without binder is analysed. Waste engine oil as an additive/binder is used. Experimental investigation for air and air–steam gasification is applied and compared. Product gas constituents, hydrogen production is examined with different steam to biomass (S/B) ratio and equivalence ratio. The equivalence ratio varies from 0.20 to 0.40 and the S/B ratio between 0 and 4. The waste engine oil (5 and 10 wt%) is mixed with the biomass during palletization. Results show maximum H₂ production and HCV of product gas at an air to fuel of 0.26 and 2.4 steam to biomass ratio. This study considers the rarely studied Indian biomasses with waste engine oil as an additive for hydrogen-rich product gas production having small scale biomass gasifier.

Graphical Abstract

Extended author information available on the last page of the article
Keywords Downdraft biomass gasifier · Product gas · Kasai saw dust · Lemon grass · Wheat straw · Pigeon pea seed coat · Steam to biomass (S/B) ratio · Equivalence ratio · Waste engine oil

List of Symbols
A  Air
a, b, c, d and e  Coefficients of elements of the product.
AR Pre-exponential factor, k mol m⁻³ s⁻¹
C Carbon
Ch₂ Methane
CO Carbon mono oxide
C_RF Char reactivity factor
ER Equivalence ratio
E_Ri Activation energy, J mol⁻¹
F Fuel
FC Fixed carbon
H Hydrogen
hfg Enthalpy difference between gas and fluid
HCV Higher calorific value
HHV Higher heating value
K Equilibrium constants
LCV Lower calorific value
LHV Lower heating value
ln Natural logarithm
m Quantity of oxygen per k mol of biomass
M Molar mass
MC Moisture content
nᵢ Number of species in mole
n_tot Total number of all species in product gas in moles
O Oxygen
Q_PG Calorific value of product gas
r Quantity of water per k mol of biomass
R Gas constant
S Sulphur
S/B Steam to biomass ratio
T Temperature
U Constant of integration
V Constant
VM Volatile matter
W, X, Y, Z Heat capacities
WEO Waste engine oil
ΔG₀ Standard Gibbs function of formation
ΔH₀ Heat of formation

Statement of Novelty

Waste biomasses are abundant in agricultural-producing countries such as India, China, United States and Brazil, and can be a suitable source of clean energy to meet demand on a local scale. The current research focuses on increasing H₂ yields using a small-scale biomass gasifier that may be deployed in farms and used, while lowering production costs. The majority of past research focused on either air or steam gasification, but air–steam gasification is now being explored to determine the best ratio. Previous research has found that biomasses evaluated for this study are scarce, if not non-existent. To the best of our knowledge, waste engine oil as an additive is likewise unavailable.

Introduction

Energy from biomass can be considered an environmentally friendly and renewable energy sources [1]. Biomass energy has a huge potential to come out with the world’s energy demand while without increasing the environmental problems. The biomasses can be utilized using the various routes of thermochemical conversion process like combustion, pyrolysis, gasification and liquefaction [2]. The conversion method opted are depends on the key decision factors like category and amount of biomass, required configuration of output fuel, fuel transportation, end-user applications and infrastructure availability. For developing and agriculture-based economy like India with the increasing energy demand creates huge pressure on energy resources. India is an agricultural country with more than half of the total land as farms [3] which is approximately 2 Mkm² (60.49% of land area) [4]. The availability of agricultural wastes, wastes after food processing industry is in huge amount and this should be utilized as much as possible to cope up with energy demand without depending on fossil fuel. In the year 2020, it is estimated in another study around 5 × 10⁹ metric tons annually by Kumar et al., 2020 [5].

The main issue with biomass utilization is the lack of infrastructure, which necessitates a significant investment. Small-scale gasification plants, rather than large biomass plants, may be the best solution. Various researchers have carried out their work considering either small scale or pilot scale gasification systems [6–10]. The internal combustion engine set is the end application chosen by the majority of the researchers [11]. Having the higher energy per gram (i.e., 142 kJ/g), better transportation ability, environmentally supportive as it doesn’t release hydrocarbon, oxides of carbons and nitrogen, Hydrogen proves its importance in the energy field [5]. The thermochemical conversion process, which is typically used to gasify high-organic-content biomasses, can produce clean hydrogen energy. Several researches have emphasized the importance of H₂ rich producer gas production. [12–18].
Steam gasification is one of the finest solutions for hydrogen-rich gasification products. Steam has been proposed as a gasifying medium for the advanced synthesis of H$_2$ or H$_2$ rich product gas by a handful of publications. Steam is employed as a heat carrier and even a gasification agent. [13]. Trabelsi et al. applied pre-treatment of feedstock prior to gasification [14]. Air, O$_2$ and steam are the common mediums for gasification. When compared to air gasification, steam gasification has some drawbacks, such as higher energy consumption, lower product LHV, and the need for an external heat source. Some researchers used steam gasification to conduct their studies for hydrogen-rich gasification product. Lv et al. applied the air and O$_2$/H$_2$O(vapour) as gasifying agent in downdraft gasifier and observed that steam gasification is more favourable for H$_2$ rich gas production [15]. Adefeso et al. integrated the H$_2$ rich gas with fuel cell based structure [16]. Valizadeh et al. applied steam and air gasification [17]. Rakesh and Dasappa utilized O$_2$/H$_2$O(vapour) as the gasification medium for downdraft gasifier and analyse the tar collected [19].

Different species have different composition of Syngas after gasification. There are different types of Indian biomass like Bamboo, Gulmohur, Dimaru, Shisham/Sesame, Neem wood [20, 21] Babul wood [22], Mango Wood, Tung shells [23] Bagasse, Jatropha shells [24], Pongamia residue [25], garden waste [26] are considered for study by the researchers. Still a lot of agricultural by-products, forest and processing industry wastes are required to examined.

Inclusion of additives are favourable for improvement of quality and composition of syn-gas, some additives also worked as binders. Gonzalez et al. used glycerol (varying between 0 and 5wt%) as a binder for fallen leaves biomass and observed increment of CH$_4$ by 25% and H$_2$ by 20% compare to biomass without a binder [27]. Shone and Jothi considered the leaves of Teak and Rubber tree having tapioca starch as a binder at different biomass to binder ratio [28]. Nobre et al. used Refuse derived fuel char with 0, 5 and 10% incorporation as additive with Pine waste biomass for gasification [29].

Most of the gasifier working in India are downdraft gasifiers and considered mostly for woody biomass [30]. Given the above context, in the present analysis, four different central Indian based biomasses Kasai (Pometia pinnata) sawdust, as woody biomass waste, lemongrass as grasses, wheat straw as wastes left on the agricultural land, pigeon pea (Cajanus cajan) seed coat as the food processing industry wastes are considered. The biomasses considered are from different group of biomasses production system i.e., Woody biomass waste, Grasses, Agricultural wastes and Food processing industry wastes. One of the biomasses from each section which is available in a huge quantity is considered. The present study concern for increasing the H$_2$ yields having small scale biomass gasifier as it can be installed in farms and wastes can be utilized in all over the world. Each of the biomass considered for the study is available in large amount and required to be treated well. Apart from all this waste automotive engine oil is utilized as additives which also acts as binders and reduced the friction during the palletization process. In countries like India where automobiles are huge in number and waste engine oils are required to recycle to save the environment pollution. Thus, it will be beneficial as it can be utilized as binder. The information in literature for biomasses considered for the present work is rare even not available for some biomasses. The use of waste engine oil as the additive is also not available in the literature, best of our knowledge. There is rare information even not for some biomasses are available in the literature. The waste engine oil as the additive is also not available in the literature, best of our knowledge.

The aim of the current analysis is concentrated on the production of H$_2$ rich product gas based on air and air–steam gasification of Kasai Sawdust, Lemon-Grass, Wheat Straw and Pigeon Pea Seed Coat biomasses with waste automotive engine oil as additive or binder for downdraft gasification system. For the analysis, Down-draft fixed bed gasifier is considered due to its advantages of low tar generation, compatibility with pallets, accessible gasification temperature.

### Process Modelling

It is a renowned reality that in biomass gasification four regions i.e., drying, pyrolysis, combustion, and gasification are established [31]. Drying of biomass for reduction of moisture content up to 5% is taken place in the drying zone. In second region, i.e., pyrolysis, the disintegration of biomass takes place without oxygen. The pyrolysis process that takes place in the pyrolysis zone produces a mixture of CO, H$_2$, CO$_2$, hydrocarbons and solid char. During the pyrolysis, the combustion process also continues simultaneously. Both processes create a pyro-oxidation zone. In the last process, i.e., in the gasification zone, numerous reactions take place. Following reactions are prime considerations for gasification:

- **Boudouard reaction**
  \[ \text{C} + \text{CO}_2 \leftrightarrow 2\text{CO} \]  
  \[ \text{(R-1)} \]

- **Primary water–gas reaction**
  \[ \text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2 \]
  \[ \text{(R-2)} \]

- **Water–gas shift reaction**
  \[ \text{C} + 2\text{H}_2 \rightarrow \text{CH}_4 \]
  \[ \text{(R-3)} \]

- **CO + H$_2$O ↔ CO$_2$ + H$_2$**
  \[ \text{(R-4)} \]
Steam methane reforming reaction

\[ \text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2 \]  

(R-5)

Numerous researchers provide various methods for modelling biomass materials [32–37]. In a downdraft gasifier, the gasification process follows drying, flaming pyrolysis (combustion & pyrolysis) and finally the product gasified. For the process modelling, the equilibrium approach has been considered for combustion and pyrolysis while for the gasification kinetic modelling approach considered. The chemical formulae for each biomass are given in Table 3

Pyrolysis-Oxidation Zone

The comprehensive gasification reaction is as [32, 33]

\[ \text{CH}_p\text{O}_q + r\text{H}_2\text{O} + m\text{O}_2 + 3.76m\text{N}_2 \rightarrow a\text{H}_2 + b\text{CO} + c\text{CO}_2 + d\text{H}_2\text{O} + e\text{CH}_4 + 3.76m\text{N}_2 \]  

(R-6)

The values of quantity of water per kmol of biomass (r) can be calculated as:

\[ r = \frac{\text{Moisture Content}}{(100 - \text{MC}) \times (100 - \text{Ash})} \times \frac{M_{\text{fuel}}}{M_{\text{H}_2\text{O}}} \]  

(1)

M stands for molar mass. By considering the mass balance equations for hydrogen, carbon, and oxygen

\[ 1 = b + c + e, \text{ based on C balance} \]  

(2)

\[ 2r + 1.44 = 2a + 2d + 4e, \text{ based on H balance} \]  

(3)

\[ r + 0.66 + 2m = b + 2c + d, \text{ based on O balance} \]  

(4)

Equation (R-2) shows the methane formation while (R-3) shows the shift reaction. The equilibrium constants are as

\[ K_1 = \frac{P_{\text{CH}_4}}{(P_{\text{H}_2})^2} = \frac{e}{a^2} \]  

(5)

\[ K_2 = \frac{P_{\text{CO}} P_{\text{H}_2}}{P_{\text{CO}_2} P_{\text{H}_2}\text{O}} = \frac{a \times c}{b \times d} \]  

(6)

The heat balance equation for the process

\[ \text{d}H_{\text{biomass}} + r\text{d}H_{\text{H}_2\text{O}(l)} = a\text{d}H_{\text{H}_2} + b\text{d}H_{\text{CO}} + c\text{d}H_{\text{CO}_2} + d\text{d}H_{\text{H}_2\text{O}(vap)} + e\text{d}H_{\text{CH}_4} + 3.76m\text{d}H_{\text{N}_2} \]  

(7)

The equilibrium constant K can be given as [32]

\[ -RT \ln K = \Delta G^0 \]  

(8)

Here \( \Delta G^0 \) is the standard Gibbs function of formation. The relation between Heat of formation \( \Delta H^0 \), Standard Gibb’s function \( \Delta G^0 \) is

\[ \frac{d}{dT} \left( \frac{\Delta G^0}{RT} \right) = -\frac{\Delta H^0}{RT^2} \]  

(9)

\[ \frac{\Delta H^0}{R} = V + \frac{\Delta W}{T} + \frac{\Delta X}{2T^2} + \frac{\Delta Y}{6T^3} - \frac{\Delta Z}{T} \]  

(10)

From Eq. (9) and (10)

\[ \ln K = -\frac{V}{RT} + (\Delta W)\ln T + \frac{\Delta X}{2T^2} + \frac{\Delta Y}{6T^3} + \frac{\Delta Z}{2T^2} + U \]  

(11)

And standard Gibb’s function \( \Delta G^0 \) can be given as

\[ \Delta G^0 = V - RT \left( (\Delta W)\ln T + \frac{\Delta X}{2T^2} + \frac{\Delta Y}{6T^3} + \frac{\Delta Z}{2T^2} + U \right) \]  

(12)

W, X, Y and Z are the heat capacities [33]. The values can be calculated using Tables 1 and 2.

The set of Eqs. (2)–(7) can be solved to find out the value of a, b, c, d and e. For finding out the value of constants \( K_1 \) and \( K_2 \), Eq. (11) at specific temperature of reactions can be utilized. The thermodynamic properties can be obtained from [33].

The exit value of species amounts, and thermal properties of present region are considered as input parameter to the next region. Reactions R-1, 2, 3 and 5 are considered for

Table 1 Heat capacities of different species (calculation for \( \Delta W, \Delta X, \Delta Y \) and \( \Delta Z \))

| Species               | Maximum temperature | W     | X     | Y     | Z       |
|----------------------|---------------------|-------|-------|-------|---------|
| Methane              | 1500                | 1.702 | 0.009081 | -0.000002164 |
| Hydrogen             | 3000                | 3.249 | 0.000422 | 8300 |
| Carbon mono oxide    | 2500                | 3.376 | 0.000557 | -3100 |
| Carbon dioxide       | 2000                | 5.457 | 0.001047 | -115,700 |
| Nitrogen             | 2000                | 3.28  | 0.000593 | 4000 |
| Water                | 2000                | 3.47  | 0.00145 | 12,100 |
CH₂O₂ + r₁(γ)H₂O + r₂(γ)H₂O + mO₂ + 3.76mN₂ → aH₂ + bCO + cCO₂
+ dH₂O + eCH₄ + 3.76mN₂  \tag{R-7}

In equation (R-7) the term \( r_{(γ)} \) is known as steam to biomass (S/B) proportion which is in terms of molar ratio of corresponding values \([39]\). For modelling of steam gasification process the value of \( r_{(γ)} \) need to consider in Eq. (3), (4) and (7) and will be counted for further calculation.

### Materials and Methods

Biomass basically can be categorized as Hard-Stemmed plants, vascular plants and grasses, marine plants, farming and food industry wastes. For the present analysis, wide range of waste biomass considering all the categorizations available in the central India region except the aquatic plants. Kasai (Pometia Pinnata) sawdust is considered as woody biomass waste, Lemon Grass is considered as Grasses and Wheat straw as the agricultural wastes and pigeon pea (Cajanus cajan) seed coat as food industry waste are considered. Apart from all this, waste automotive engine oil is utilized as additives or binders. The Kasai sawdust is obtained from the shiv wood timber cutting plant, Jabalpur M.P. (India). The Lemon Grass, Wheat straw are collected from the farms near Jabalpur. The lemon grass wastes are the residue after oil removal while the wheat straw is the wastes obtained after processing. Pigeon pea also known as Arhar seed coats are obtained from the local mill used by farmers. The waste engine oil is obtained from the automobile servicing centre. All the biomasses collected are shown in Fig. 1. The Fig. 2 shows the biomasses in powder form.
Palletization of Biomass Waste

For converting the biomass in suitable form as a feedstock pre-treatment is carried out which includes size reductions, solar drying and densification using palletization [38]. Palletization is a densification process, carried out by cylinder-piston type die pressing. It contains a cylinder having internal radius of 5 cm and 30 cm height. A die plate with a smaller diameter was used to produce pellets from which pressed biomass extruded. Initially, the biomass is sundried, crushed and sieved in a laboratory in the form of fine powder for having dimensions less than 200 mesh size (i.e., 74 μm). The sieved biomass is again oven-dried for up to 1 h for removal of moisture particles if any. Biomass (95% by weight) with waste lubricating oil (5% weight) as a binder is mixed manually and separately. The mixed proportion is thus compressed using the cylinder-piston type die pressing machine (Fig. 3). The mixed proportion is thus extruded with the speed of 2 mm/second extrusion of biomass pellets.

Characterization of Biomass

The characterization of biomass is carried out with the help of proximate and ultimate investigation of the biomass with and without the binder. The proximate analysis is carried out for estimation of FC, Moisture, VM and Ash while the
ultimate analysis is carried out for C, H, N, S and O content in the biomass. The ratio of feedstock to binder is considered as 0–0.1 wt%. The proximate and ultimate analysis is carried out by adopting the IS:1360 (P-1) and (P-4, section “Introduction” and “Process Modelling”) Indian standards[41, 42]. Table 4 shows both the proximate and ultimate analysis for all the feedstock separately. Moisture content is wet basis while the others are dry basis. The lower heating value, higher heating value calculated using Eq. (17)–(18).

\[
LHV_{\text{biomass}} = HHV_{\text{biomass}} - hf_g(H + M)
\]  

(17)

The higher heating value can be estimated using [43, 44]

\[
HHV_{\text{kg}} = 0.3383C + 1.443\left(H - \frac{O}{8}\right) + 0.0942S
\]  

(18)

Though numerous relationships are existing for biomasses, Vargas-Moreno et al. [44] proposed a relation that is appropriate for inclusive diversity of plant types:

\[
HHV_{\text{kg}} = 0.3491C + 1.1783H - 0.1034O + 0.1005S - 0.0151N - 0.0211\text{Ash}
\]  

(19)

**Experimental Analysis**

A detailed experimental analysis considering 4 biomasses with different percentage of binders have been carried out. The experimental system (Fig. 4) comprises downdraft biomass gasifier of inside diameter of 665 mm, 0.25 mm thickness and height if about 2110 mm. The throat diameter is about 200 mm. Air blower with the specification of 220–240 V, 500 W, 0–16,000 RPM and 6 different speed characterization is employed for induction forces and creation of negative pressure inside the chamber for air supply. The total number of 6 nozzles of 1 cm inside and 0.5 mm outside diameter are employed radially in the chamber and supply tubes are touching the gasifier combustion zone provides the air preheating effect. For measurement of air velocity, an air anemometer with the threshold of 0.3 and accuracy of ± 3% ± 0.1 is installed. Total 5 S-type thermocouples with the range of 200–1600 °C, accuracy up to 0.25% are installed in each zone. The thermocouples are installed at 2000, 1135, 710, 470, 150 mm height from the bottom. A multichannel digital temperature indicator with accuracy ±0.1 °C is installed in connection with thermocouples. A proper arrangement is made that the unused heat of product gas is used for moisture removal of pallets during feeding. For starting of biomass gasifier, initial temperature is required which is attend by combustion of pulverized coal. As the combustion occur the temperature inside the gasifier cylinder which can be measured using a thermocouple installed is elevated gradually. When the temperature is sufficiently high (almost 1180 K), weighed pallets gasifying agents are started to supply. For commercialized biomass gasifier another medium of initial heat source can be adopted. After 10–15 min the sample of gas generated is collected from the nozzle and tested by the gas analyser. This arrangement of the experiment is repeated for each sample. Collection of ash, feeding of biomass pallets are carried out using grate and hopper respectively. An electric coil heating device is also installed with a pipe supply for steam generation and transportation at temperature up to 1100 K and pressure up to 0.4 MPa.

The equivalence ratio (ER) is the prime considered parameter as it greatly affects the outcome of the gasification processes. Some researchers have taken it in the range of (0.08–0.8) [45], while some varied it is only a small range (0.12–0.4) [12, 16]. For the present study, the ER is changes from 0.2 to 0.4. The ER is controlled using a flow valve and anemometer. The air flow rate variation is given in Table 5.

| Biomass                  | C   | H   | N   | S   | O   | FC  | VM  | Ash | MC | Chemical Formulae Molecular weight gm/mol | Calorific Value |
|-------------------------|-----|-----|-----|-----|-----|-----|-----|-----|----|------------------------------------------|-----------------|
| Kasai wood dust (Pometia Pinnata) | 50.3| 6.24| 0.12| 0.02| 43.2| 13.8| 70.1| 1.1 | 15 | CH₄O₃N₀̷₄N₀̷₀₂ | 34.12           | 17.207          |
| Lemon Grass             | 41  | 6.1 | 1.54| 0.01| 51.3| 24.8| 60  | 7.21| 8.02| CH₃CO₂H₀₃₂N₀̷₀₂ | 44.32           | 13.858          |
| Wheat Straw             | 48  | 5.5 | 0.44| 0.16| 45.9| 10.5| 72.5| 6.93| 10 | CH₃O₂₂H₀₂₃N₀̷₀₀₈ | 36.46           | 16.246          |
| Pigeon Pea (Cajanus cajan) Seed Coat | 45.6| 7.53| 0.82| 0.12| 45.8| 17  | 71  | 4.82| 7.2 | CH₄O₂₃N₀̷₅N₀̷₀₁₅ | 38.3            | 15.749          |

Table 4 Ultimate and proximate analysis of the biomasses
As various researchers found this range as optimum range, the range of steam to biomass ratio (SBR) is considered from 0 to 3, with the value of 0, 0.8, 1.6, 2.4 and 3 [15, 19, 46]. A flow meter is employed to quantify the steam movement. While varying the steam supply, the air supply is kept constant. After 15–20 min, a bluish-green colour flame is generated which shows the good quality of product gas. Throughout the experimentation procedure, the values obtained were repeated three times, and the average data was used for analysis.

Stoichiometric air-to-fuel ratio and calorific value of product gas are found out by formulae recommended by Basu [2] and Prasad [24] respectively.

\[
\left( \frac{A}{F} \right)_{st} = (0.1153 \times C) + (0.3434 \times (H - \left( \frac{O}{8} \right))) + (0.0434 \times S) \tag{20}
\]

\[
Q_{PG} = \frac{(b \times CV_{of\ CO}) + (a \times CV_{of\ H_2}) + (e \times CV_{of\ CH_4})}{100} \tag{21}
\]

### Results and Discussion

The thermocchemical conversion for different required products has different aspects or parameters like temperature, ER etc. of reaction stages and named gasification, pyrolysis and torrefaction. For the gasification process, pyrolysis is one of the stages which contains the vary little or absence of oxygen and products partially removed carbon without the addition of hydrogen. In complete gasification, oxidising agents like steam, air are used to produce the chemical bonds that can release energy after oxidization [47–49].

The experimentation has been performed in two stages in which the air and steam gasification both are performed for the same biomass and the results are compared based on syngas composition, hydrogen yield and other performance parameters considering the ER and S/B ratio as the prime considerations.

### Temperature Distribution in the Gasifier

The temperature is obtained from the thermocouple installed at 15 min during the gasification process of all the four feedstocks Kasai sawdust, lemongrass, wheat straw and pigeon pea seed coat for ER of 0.2, 0.26, 0.33 and 0.398 are depicted in Fig. 5. There is specific temperature at which bonds breaks and it is different for all the materials.

The temperature inside the reactors depends on the equivalence ratio. It can be observed for all the four feedstocks that the temperature of the oxidation–reduction region is maximum for ER 0.26, while it starts decreasing on further increment in ER. For lower equivalence ratio i.e., 0.2 the temperature is in between 625 and 825 °C, it is maximum of about 800–1000 °C for the ER 0.26 and starts again decreasing on the further increment of ER. On increasing the ER from 0.2 to 0.26, oxygen availability is increased, and it releases more heat due to increment of oxidation rate. This heat increases the reactor temperature. This process is continuing as the ER increases but there is another fact that as the ER increases the supply of N₂ also increases. More N₂ behaves as heat transfer medium and diminishes the temperature inside the reactor on further increment of air supply, thus lower temperature found inside the reactor on higher ER. [9, 21, 50, 51]

The different temperature profile is obtained for the different feedstock as it based on the composition, density of...
pallets etc. The higher temperature of reduction zone is obtained for pigeon pea seed coat and it lowers for wheat straw, Kasai and lemongrass in order, but all the feedstock shows the same trends only temperature changes. The density of pallets which depends on biomass particle size itself plays a vital role as it regulates the air contact with feedstock particles. Good contacts show better efficiency of the process and higher gasification temperature.

Effect of ER on Syngas Composition, Hydrogen Yield and Other Performance Parameters

The equivalence ratio is kept between 0.2 and 0.4. If the value kept below the range pyrolysis is leading while having more than this combustion is leading. Most of the gasifiers with medium and large size are employed with a feed controlling system. For the present work, a small-scale gasifier
is used in which a controlling system over the fuel feeding is not installed but only air supply can control. The fuel feeding is kept constant at 1 kg/h and the corresponding air supply is changed through the controlling valve. It results in different air flow rate and thus, constant ER i.e., 0.2, 0.2686, 0.333 and 0.398 respectively. Assessment among the model parametric calculations and experimental results is put through for ER varies from 0.2 to 0.398. It has been observed that some deviations are between experimental and model analysis results at different ER for different feedstock, but they are not more than 15% (Fig. 6). The equilibrium model discussed in section “Process Modelling” is used for the modelling of gasification of all the biomasses. The iterations depend on steps given in section “Process Modelling” are carried out for the composition values depending upon the modelling equations. The constants values are obtained from the data given in Tables 1, 2 and 3. The model estimate values are somewhat lesser than the experimental data. 

The Equivalence ratio decides the incomplete combustion to produce gases like CO. Higher value of ER favours excess oxygen which results in CO2. The Fig. 7a–d shows the composition of CO, CO2, H2 and CH4 for considered feed (i.e., Kasai sawdust, lemongrass, wheat straw and pigeon pea seed coat) stock with varying percentage of the binder at different Equivalence Ratio. It can be observed that the composition of CO up to 18.6% for ER 0.26 when only Kasai wood dust pallet is used. It increases up to the value of 20.46 and 21.6% respectively with 5% and 10% addition of waste engine oil as the binder. For all the set of biomasses it can be observed that the maximum CO can be obtained at 0.26ER, while increasing the ER the curve starts lowering and CO2 increases which shows the conversion of CO into CO2. At the maximum value of CO, the CO2 composition shows minimum value. It can be observed that the percentage composition of CH4 also increases up to the ER 0.26 and thereafter starts decreasing. It is maximum at 0.26 ER for all set of biomasses. The binder increment also shows the increment in CH4 composition. A similar trend is observed for H2 composition. Advanced H2 and CH4 composition values were obtained corresponding to all the biomasses without and with binders at the equivalence ratio of 0.26. For Kasai it is 2.3%, 2.6% and 3.4% for without, 5% and 10% binder addition biomasses. Similarly, for Lemon Grass it is 1.7%, 2.1% and 3.1%, for Wheat Straw it is 1.7%, 1.95% and 2.4%, and for pigeon pea seed coat, it is 2.1%, 2.4% and 3%, respectively for without, 5% and 10% binder addition.

The composition of CO, CO2, H2 and CH4 are greatly affected by ER. At the lower value of ER, the oxygen supply is not sufficient that initial reactions generate sufficient heats for further processing. The increment in ER also increases the supply of O2, which enhances the exothermic combustion reaction, which helps the increment of gasifier bed temperature. The higher temperature intern supports the endothermic reactions. Reactions R-1, R-4 and R-3 enhance the H2 and CO compositions in the cost of CO2 composition. For the higher value of ER, complete combustion of residues enhances which generates CO2 instead of CO, which intern decreases the net calorific value of product gas. Thus, it is required to have ER in optimum value, which changes with each material as different materials have different compositions [52–54].

If energy released per kg of biomass is considered, pigeon pea seed coat produces maximum energy among the set of biomasses when using without binders. Pigeon pea seed coat released 10.94 MJ/kg of biomass energy. While in addition with 5% and 10% binders it released 12.03 and 13 MJ/kg of biomass energy respectively. Kasai

![Fig. 6 Experimental and model analysis results for composition of hydrogen of different feedstock without addition of binder](image-url)
Fig. 7  Product gas composition for different feed stock with varying percentage of binder and different Equivalence Ratio
sawdust without and with 5% and 10% waste engine oil releases 10.7, 11.9 and 13.11 MJ/kg of biomass energy. 9.81, 10.4, 11.95 MJ/kg of biomass and 10.23, 11.32, 12.42 MJ/kg of biomass are the values of energy released by the lemongrass and wheat straw without and with 5% and 10% waste engine oil respectively.

The highest average calorific value of product gas is gotten from gasification of pigeon pea seed coat with 10% waste engine oil as a binder is 6.256 MJ/Nm³ with an ER of 0.26. It perhaps analysed that the increment of waste engine oil also increases the calorific value of product gas.

It can be observed from the Fig. 8 that the LHV is maximum for ER 0.26 for all the biomasses. The Fig. 8 is shown without considering the steam injection and for biomasses without waste engine oil. The LHV is maximum for pigeon pea seed coat pallets and it followed by Kasai wood dust, wheat straw and lemongrass respectively. The maximum lower heating value of the product gas from pigeon pea seed coat, Kasai wood dust, wheat straw and lemongrass are 5.63, 5.09, 4.96 and 4.47 MJ/Nm³ respectively. The LHV depends on the volume fraction of CO, H₂, and CH₄ which are considerably lesser than the volume fractions in the product gas generated from Kasai wood dust, wheat straw and lemon grass compare to pigeon pea seed coat as can be seen in Fig. 7.

**Effect of S/B Ratio on Syngas Composition, Hydrogen Yield and Other Performance Parameters**

The steam and biomass proportion affects the configuration of product gas. As keeping the biomass and air (constant ER 0.26) supply constant, the steam supplies vary for changing the S/B ratio. As the steam supplies more than its optimum requirement it uses the heat for superheating thus temperature in gasification zones is reduced and results in a reduction in yielding of hydrogen and carbon mono oxide and higher composition of H₂O in the product gas [39]. The higher percentage of steam proceeds to R-4 and R-5 which increases both CO₂ and CO, but due to lowering the temperature CO compositions reduces due to endothermic reactions.

For having the experimental results for the observation of the impact of steam and biomass proportions, the S/B ratio ranges from 0 to 3, with the value of 0,0.8,1.6,2.4 and 3, while keeping the ER constant at 0.24. For the experiments using air and biomasses, it can be observed that the steam addition increased the H₂ concentration (14.2–30.7 vol.% for Kasai wood dust, 13.7–29.6 vol.% for lemongrass, 21–45.4 vol.% for wheat straw and 18–38.9 vol.% for pigeon pea seed coat) while the composition of CO (18.6–13 vol.% for Kasai wood dust, 14–10.69 vol.% for lemongrass, 14.7–10.5 vol.% for wheat straw and 15.4–11.01 vol.% for pigeon pea seed coat) decreased. The increment in H₂ is because of the increasing rate of the water gas shift reaction at cost of CO.

For the composition of CH₄ it is observed that the composition increases not much but continue almost like those found with only air. Figure 9 shows the Product gas
Fig. 9  Product gas composition for different feed stock with varying percentage of binder and different Steam to Biomass Ratio
composition for different feedstock with varying percentage of binder and different S/B Ratio.

It is evident that the addition of binders helps to increase the \( H_2 \) and \( CH_4 \) yields as compared to without the addition of binders. The \( H_2 \) starts increasing as the Steam to Biomass ratio increases. All the set of biomasses shows the higher value of \( H_2 \) yields when the S/B ratio is about 2.4 after that it starts declining. For the set of biomasses with the addition of 5% waste engine oil, \( H_2 \) yields increase up to 32.5% for Kasai wood dust, 47.6% for pigeon pea seed coat, 31.1% for lemongrass and 40.8% for wheat straw at 2.4 S/B ratio. Similarly, with the addition of 10% waste engine oil, \( H_2 \) yields increases up to Kasai wood dust 33.5%, 49.5% for pigeon pea seed coat, 32.4% for lemon grass and 42.5% for wheat straw at 2.4 S/B ratio.

It can be observed that for constant ER the value of LHV is increasing after a small amount of decrement while increasing the S/B ratio. It is maximum at 2.4 thereafter it again starts decreasing as it depends on important fraction of CO, \( H_2 \) and \( CH_4 \). This conclusion also observed in the experimental work carried out by Lv et al. [15]. The Fig. 10 considered the values for biomasses without binders. Based on experimental data, it is found that the biomasses with an increased amount of waste engine oil shows the same trends but with more LHV corresponding to the same biomass without binder. It is evident that at an S/B ratio 0.8, the calorific value is the least (i.e., 5.09, 5.75 and 6.29 MJ/Nm\(^3\) for Kasai wood dust, 4.47, 4.85 and 5.59 MJ/Nm\(^3\) for lemongrass, 4.96, 5.57 and 6.12 MJ/Nm\(^3\) for wheat straw and 5.63, 6.41 and 6.93 MJ/Nm\(^3\) for pigeon pea seed coat with 0, 5 and 10% WEO respectively). With the increment in the S/B ratio at 2.4, the LHV reaches to a maximum of (i.e., 6.97, 7.46 and 8.14 MJ/Nm\(^3\) for Kasai wood dust, 6.28, 6.77 and 7.66 MJ/Nm\(^3\) for lemongrass, 7.42, 7.98 and 8.53 MJ/Nm\(^3\) for wheat straw and 8.53, 9.17 and 9.77 MJ/Nm\(^3\) for pigeon pea seed coat with 0, 5 and 10% WEO respectively) and then follows the decreasing trend. The growing and declining tendency of LHV difference is closely that of CO and \( H_2 \) difference with S/B ratio.

**The Gasification Efficiency or Coefficient of Thermal Conversion**

The performance assessment of the downdraft biomass gasifier is estimated in terms of in coefficient of thermal conversion or cold gas efficiency. The gasification efficiency also called cold gas efficiency is the percentage ratio of product gas energy to the input biomass energy. The variation in coefficient of thermal conversion (i.e., ratio of product gas energy to the input biomass energy) with respect to ER and S/B ratio has been observed (Fig. 11). The maximum coefficient of thermal conversion can be obtained at 0.26ER and 2.4 S/B ratio. The product lower heating value is also maximum at the same data. Waste engine oil makes the same effect with and without addition, as discussed earlier. After the value of 0.26 ER, the coefficient of thermal conversion decreases. It is maximum at 0.26 ER. The same trends can be observed for S/B ratio. The maximum coefficient of thermal conversion obtained at 0.24 S/B ratio and it decreases after that.

**Effect of Waste Engine Oil as Binder**

In the present analysis, waste engine oil is mixed as binder with the variation of 5% and 10% by weight. Considerable changes in parameters have been observed. Addition of waste engine oil increases the \( H_2 \) yields. With the addition of 5% waste engine oil, the yield increases from 14 to 17% for kasai wood, 13–15% for wheat straw, 15.9–17.4% for pigeon pea seed coat and 5.6–6.6% for lemongrass at different ER.

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**Fig. 10** LHV of Produced gas with respect to Steam to biomass ratio at constant ER 0.24
On further increment i.e., up to 10% waste engine oil, the increment is not in same proportion, the yield addons about 3–6% for kasai wood, 5–7% for wheat straw, 2.3–4.8% for pigeon pea seed coat and 2.7–4.8% for lemon grass at different ER. The yield of CO, CH₄ and CO₂ also increases. CH₄ yield is maximum for lemon grass followed by kasai, wheat straw and pigeon pea seed coat.

The variation in steam to biomass ratio have been carried out. As the binder percentage increases, the yield of H₂, CO, CO₂ and CH₄ increases. As the steam to biomass ratio increases, the yield of each composition increases and maximum at 2.4 S/B ratio after that it decreases. The impact of changes in yield percentage can also be depicted in value of energy released per kg of biomass and it shows incremental curve. It is observed that as the waste engine oil is added as binder the lower heating value also increases. For constant ER, the addition of 5% binder, average increment in LHV value about 13% for kasai wood dust, 9% for lemon grass, 10.5% for wheat straw and 10% for pigeon pea seed coat can be observed. While considering 10% addition of binder the value addon about 9.5% for kasai wood dust, 15% for lemon grass, 9.7% for wheat straw and 7.8% for pigeon pea seed coat.

**Economic Analysis**

On the basis of economic analysis carried out by various researchers a brief economic analysis has been carried out [55–58]. A small-scale gasification plant consists of a feeding system, gasifier section, cleaning section and water treatment section. Some auxiliaries are also required. With biomass feed rate considering 100 kg/h, 56–65 kWh with air gasification system and 77.2–89 kWh with air–steam gasification, electrical energy can be obtained, after the product gas combustion is taking place in IC engine. After the estimation of cost of consultancy/design, construction, fuel treatment electrical/balance of plant and converter system (gasifier), the plant total for the air gasification ranges from the 10,200 US $/kW to 12,400 US $/kW, while for air steam gasification, 8500 to 10,100 US $/kW. Another end application can consider, production of syngas, bio diesel and bio hydrogens, for which the

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*Fig. 11* Coefficient of thermal conversion (cold gas efficiency/100) variation with respect to the ER and S/B ratio
0.3–0.4 US $/litre investment is required. The investment and operating cost can vary depends on the location, biomass availability, transportation cost, labour cost.

**Conclusion**

In the present analysis work, an experimental study along with validation of parametric results has been carried out for four different biomasses i.e., Kasai wood dust, Lemongrass, Wheat Straw and Pigeon Pea Seed Coat with and without the waste engine oil as binder/additive. The thermochemical conversion process has been considered with downdraft gasifier as the reactor. The following conclusions have been drawn:

- Hydrogen yield by volume has been enhanced is air-steam gasification as compared to air gasification through thermochemical energy conversion gasification process.
- The H2 concentration is increases as 14.2–30.7 vol.% for Kasai wood dust, 13.7–29.6 vol.% for lemongrass, 21–45.4 vol.% for wheat straw and 18–38.9 vol.% for pigeon pea seed coat by injection of steam.
- With the increment of S/B proportion, the heating value also increases. The increment of LHV is about 19.9% for Kasai sawdust and it is a maximum of about 24.9% for pigeon pea seed coat. At the current working situations, the H2 generation just doubles at S/B ratio of 2.4, compared to without injection of steam. Without binder condition, it is maximum i.e., 45.4 vol.% for pigeon pea seed coat and minimum for lemongrass about 29.6 vol.%.
- The affecting behaviour of equivalence ratio on experimental results indicates that an optimum value of 0.26, the hydrogen yield is maximum for all the biomass sets. The lower heating value is also maximum at 0.26 equivalence ratio.
- The results obtained are compatible with parametric results and results obtained from other studies.
- The effect of waste engine oil addition with the biomasses is favourable. The hydrogen yields and LHV of the product gas are found additional compared to the biomasses without the addition of the waste engine oil.

**Data Availability** All data generated or analyzed during this study are included in this published article [and its supplementary information files]. If reader still need certain data which are not included in manuscript, are available from the corresponding author on reasonable request.

**Declarations**

**Conflict of interest** The authors have not any conflict of interest in the subject matter or material discussed in this manuscript.

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