

# Hydrogen rich product gas from air-steam gasification of Indian biomasses with waste engine oil as binder

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## Research 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

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# “Hydrogen rich product gas from air-steam gasification of Indian biomasses with waste engine oil as binder”

## Abstract

Present study concerns with the production of H<sub>2</sub> rich product gas by thermochemical energy conversion having biomass gasification as a route for the four biomasses i.e., Kasai Saw Dust, Lemon Grass, Wheat Straw and Pigeon Pea Seed Coat. The biomasses are from the family of woody biomass, grasses, agricultural waste and food process industry wastes. Waste engine oil as an additive is used, which also acts as a binder. Air gasification and Air-steam gasification is applied and compared for product gas composition, hydrogen yield and other performance parameters like lower heating value, energy yield. Product gas constituents, hydrogen production is examined with different steam to biomass ratio (S/B ratio) and equivalence ratio. The equivalence ratio varies from 0.20-0.40 and the steam to biomass ratio varies between 0-4. The waste engine oil is mixed with the biomasses with different percentage of 5 and 10 wt%. For enhancement of feedstock quality palletization process is applied. The H<sub>2</sub> yield is greatly affected by the equivalence ratio. Results show maximum H<sub>2</sub> production and higher calorific value of product gas at an air to fuel of 0.26 for all the biomass pallets. Also, the S/B ratio observed as important aspect for hydrogen enrichment. Hydrogen yield is maximum at 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 and will be beneficial for small scale hydrogen-rich syngas production considering the central Indian region originated biomasses.

**Statement of Novelty (SON):** Research work belongs to eco-friendly use of rarely studied Indian biomass pallets. Equivalence air to fuel ratio (E/R ratio), steam to biomass ratio (S/B ratio) and waste engine oil as additive have been considered to upgrade H<sub>2</sub> content and Calorific Value (CV) of the product gas. Novelty of work include use of waste engine oil as additive to make biomass pallets.

**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.

## 1. 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 Mkm<sup>2</sup> (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 2015, it is estimated in another study around 5×10<sup>9</sup> metric tons annually by A Kumar et al, 2015 [5].

The basic problem of utilization of biomass is the infrastructure availability, as it required immense investment. Rather than applying huge biomass plants, small scale gasification plants can be the best solution. Various researchers have carried out their work considering either small scale or pilot scale gasification systems [5]–[9]. The end application selected by most of the researchers are the internal

combustion engine set [10]. 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 [11]. Clean hydrogen energy can be generated via the thermochemical conversion route, usually by gasification of biomasses having high organic content. Various researchers emphasise H<sub>2</sub> rich producer gas production [12]–[18].

For hydrogen-rich gasification product, steam gasification is one of the best options. Various researchers suggest steam as a gasifying medium for advanced creation of H<sub>2</sub> or H<sub>2</sub> abundant product gas. Steam is used as a gasification agent as well as a heat carrier [13]. Trabelsi et al., 2007 applied pre-treatment of feedstock prior to gasification [14]. Air, O<sub>2</sub> and steam are the common mediums for gasification. Compare through air gasification, steam gasification having some limitations like more energy consumption, LHV of the product, external heat source etc. Some researchers carried out their research for hydrogen-rich gasification product considering steam gasification. Lv et al., 2007 applied the air and O<sub>2</sub>/H<sub>2</sub>O(vapour) as gasifying agent in downdraft gasifier and observed that steam gasification is more favourable for H<sub>2</sub> rich gas production [15]. Adefeso et al., 2015 integrated the H<sub>2</sub> rich gas with fuel cell based structure [16]. S. Valizadeh et al., 2021 applied steam and air gasification [17]. Rakesh & Dasappa, 2018 utilized O<sub>2</sub>/H<sub>2</sub>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 examine.

Inclusion of additives are favourable for improvement of quality and composition of syn-gas, some additives also worked as binders. Gonzalez et al 2019, used glycerol (varying between 0-5% wt.) as a binder for fallen leaves biomass and observed increment of CH<sub>4</sub> by 25% and H<sub>2</sub> by 20% compare to biomass without a binder[27]. Shone & Jothi, 2016 considered the leaves of Teak and Rubber tree having tapioca starch as a binder at different biomass to binder ratio[28]. Nobre et al., 2020 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. Apart from all of this waste automotive engine oil is utilized as additives which also acts as binders and reduced the friction during the palletization process. 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<sub>2</sub> 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.

## **2. Process Modelling**

The thermochemical 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[31]–[33].

It is a renowned reality that in biomass gasification four regions i.e., drying, pyrolysis, combustion, and gasification are established [34]. 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 taken place in the pyrolysis zone produces a mixture of CO, H<sub>2</sub>, CO<sub>2</sub>, 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



Primary water–gas reaction



Water–gas shift reaction



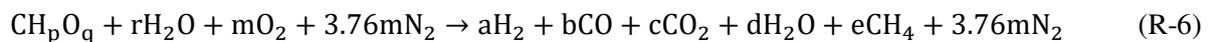
Steam methane reforming reaction



Numerous researchers provide various methods for modelling biomass materials [35]–[40]. 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

(a) Pyrolysis-oxidation Zone

The comprehensive gasification reaction is as [35], [36]



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

$$r = \frac{\text{Moisture Content}}{(100-MC) \times (100-Ash)} \times \frac{M_{\text{fuel}}}{M_{H_2O}} \quad (1)$$

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

$$1 = b + c + e, \quad \text{based on C balance} \quad (2)$$

$$2r + 1.44 = 2a + 2d + 4e, \quad \text{based on H balance} \quad (3)$$

$$r + 0.66 + 2m = b + 2c + d, \quad \text{based on O balance} \quad (4)$$

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

$$K_1 = \frac{P_{CH_4}}{(P_{H_2})^2} = \frac{e}{a^2} \quad (5)$$

$$K_2 = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} = \frac{a \times c}{b \times d} \quad (6)$$

The heat balance equation for the process

$$dH_{\text{biomass}} + rdH_{H_2O(l)} = a dH_{H_2} + b dH_{CO} + c dH_{CO_2} + d dH_{H_2O(vap)} + e dH_{CH_4} + 3.76mdH_{N_2} \quad (7)$$

The equilibrium constant K can be given as [36]

$$-RT \ln K = \Delta G^0 \quad (8)$$

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

$$\frac{d\left(\frac{\Delta G^0}{RT}\right)}{dT} = \frac{-\Delta H^0}{RT^2} \quad (9)$$

and

$$\frac{\Delta H^0}{R} = \frac{V}{R} + (\Delta W)T + \frac{\Delta X}{2}T^2 + \frac{\Delta Y}{6}T^3 - \frac{\Delta Z}{T} \quad (10)$$

From equation (9) and (10)

$$\ln K = \frac{-V}{RT} + (\Delta W)\ln T + \frac{\Delta X}{2}T + \frac{\Delta Y}{6}T^2 + \frac{\Delta Z}{2T^2} + U \quad (11)$$

And standard Gibb's function  $\Delta G^0$  can be given as

$$\Delta G^0 = V - RT \left( (\Delta W)\ln T + \frac{\Delta X}{2}T + \frac{\Delta Y}{6}T^2 + \frac{\Delta Z}{2T^2} + U \right) \quad (12)$$

W, X, Y and Z are the heat capacities. The values can be calculated using table 1 and 2.

Table 1. Heat capacities of different species (calculation for  $\Delta W$ ,  $\Delta X$ ,  $\Delta Y$  and  $\Delta Z$ ). [35]

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		-115700
Nitrogen	2000	3.28	0.000593		4000
Water	2000	3.47	0.00145		12100

Table 2. Calculation for  $\Delta W$ ,  $\Delta X$ ,  $\Delta Y$  and  $\Delta Z$  for both the reactions.

	Equations for Methane formation (R-3)	$\Delta$	Equations for Water gas shift reaction (R-4)	$\Delta$
$\Delta W$	$W_{CH_4} - W_c - 2W_{H_2}$	-6.567	$W_{CO_2} + W_{H_2} - W_{CO} - W_{H_2O}$	1.86
$\Delta X$	$X_{CH_4} - X_c - 2X_{H_2}$	0.007466	$X_{CO_2} + X_{H_2} - X_{CO} - X_{H_2O}$	-0.000538
$\Delta Y$	$Y_{CH_4} - Y_c - 2Y_{H_2}$	-0.0000022	$Y_{CO_2} + Y_{H_2} - Y_{CO} - Y_{H_2O}$	0
$\Delta Z$	$Z_{CH_4} - Z_c - 2Z_{H_2}$	70100	$Z_{CO_2} + Z_{H_2} - Z_{CO} - Z_{H_2O}$	-116400

The set of equations (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  $K_2$ , equation (11) at specific temperature of reactions can be utilized. The thermodynamic properties can be obtained from [35].

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 reduction zone. The reaction rates for these reduction zones are as [41] :

$$K_{R-1} = C_{RF}A_{R1} \exp\left(\frac{-E_{R1}}{R_m T}\right) \left[ \left(\frac{n_{CO_2}}{n_{tot}}\right) - \frac{\left(\frac{n_{CO_2}}{n_{tot}}\right)^2}{\exp\left[-\frac{2G_{T,CO}^0 - G_{T,CO_2}^0}{R_m T}\right]} \right] \quad (13)$$

$$K_{R-2} = C_{RF}A_{R2} \exp\left(\frac{-E_{R2}}{R_m T}\right) \left[ \left(\frac{n_{H_2O}}{n_{tot}}\right) - \frac{\left(\frac{n_{H_2}}{n_{tot}}\right)\left(\frac{n_{CO}}{n_{tot}}\right)}{\exp\left[-\frac{G_{T,CO}^0 + G_{T,H_2}^0 - G_{T,H_2O}^0}{R_m T}\right]} \right] \quad (14)$$

$$K_{R-3} = C_{RF}A_{R3} \exp\left(\frac{-E_{R3}}{R_m T}\right) \left[ \left(\frac{n_{H_2}}{n_{tot}}\right)^2 - \frac{\left(\frac{n_{CH_4}}{n_{tot}}\right)}{\exp\left[-\frac{G_{T,CH_4}^0 - 2G_{T,H_2}^0}{R_m T}\right]} \right] \quad (15)$$

$$K_{R-5} = C_{RF}A_{R5} \exp\left(\frac{-E_{R5}}{R_m T}\right) \left[ \left(\frac{n_{H_2O}}{n_{tot}}\right)\left(\frac{n_{CH_4}}{n_{tot}}\right) - \frac{\left(\frac{n_{CO}}{n_{tot}}\right)\left(\frac{n_{H_2}}{n_{tot}}\right)^3}{\exp\left[-\frac{G_{T,CO}^0 + 3G_{T,H_2}^0 - G_{T,CH_4}^0 - G_{T,H_2O}^0}{R_m T}\right]} \right] \quad (16)$$

$n_i$  number of species in mole

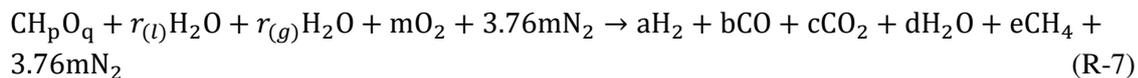
and  $n_{tot}$  total number of all species in product gas in moles

$C_{RF}$  represents the char reactivity factor, the kinetic constants of the constraints can be obtained from table 3.

Table 3. Data for reactions. [41] - [42]

Reaction	$A_R$ , pre-exponential factor, $\text{kmol m}^{-3}\text{s}^{-1}$	$E_{Ri}$ activation energy, $\text{J mol}^{-1}$
$C + CO_2 \leftrightarrow 2CO$	0.03616	77390
$C + H_2O \leftrightarrow CO + H_2$	15.17	121620
$C + 2H_2 \rightarrow CH_4$	$4.189 \times 10^{-6}$	19210
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	$7.301 \times 10^{-5}$	36150

For steam gasification the reaction (R-6) can be rewritten as



In equation (R-7) the term  $r_{(g)}$  is known as steam to biomass (S/B) proportion which is in terms of molar ratio of corresponding values [41]. For modelling of steam gasification process the value of  $r_{(g)}$  need to consider in equation (3), (4) and (7) and will be counted for further calculation.

### 3. 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 of 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 called 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 figure 1. The figure 2 shows the biomasses in powder form.



Fig. 1: Collected biomass



Fig. 2: 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 [43]. Palletization is a densification process, carried out by cylinder-piston type die pressing. It contains a cylinder having internal radius of 5cm and 30cm height. A die plate with a smaller diameter was used for the production of pallets 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 $\mu$ m). The sieved biomass is again oven-dried for up to 1 hour 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 (figure 3). The mixed proportion is thus extruded with the speed of 2mm/second extrusion of biomass pellets.

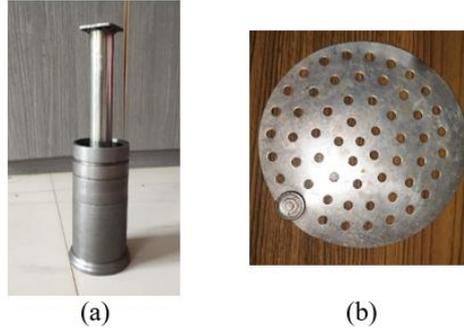


Fig. 3: Biomass palletizing arrangement (a) piston cylinder (b) Die.

### 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 1 & 2) Indian standards[44], [45]. Table 4 shows both the proximate and ultimate analysis for all the feedstock separately. The lower heating value, higher heating value calculated using equation (17-18)

Table 4. Ultimate and proximate analysis of the biomasses.

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	$CH_{1.47}O_{0.64}N_{0.002}$	34.12	17.207
Lemon Grass	41	6.1	1.54	0.01	51.3	24.8	60	7.21	8.02	$CH_{1.77}O_{0.94}N_{0.032}$	44.32	13.858
Wheat Straw	48	5.5	0.44	0.16	45.9	10.5	72.5	6.93	10	$CH_{1.36}O_{0.71}N_{0.008}$	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	$CH_{1.96}O_{0.75}N_{0.015}$	38.3	15.749

$$LHV_{\text{biomass}} = HHV_{\text{biomass}} - hf_g(9H + M) \quad (17)$$

The higher heating value can be estimated using [46], [47]

$$HHV \left( \frac{MJ}{kg} \right) = 0.3383C + 1.443 \left( H - \left( \frac{O}{8} \right) \right) + 0.0942 S \quad (18)$$

Though numerous relationships are existing for biomasses, Vargas-Moreno et al. [47] proposed a relation that is appropriate for inclusive diversity of plant types:

$$HHV \left( \frac{MJ}{kg} \right) = 0.3491C + 1.1783H - 0.1034O + 0.1005S - 0.0151N - 0.0211Ash \quad (19)$$

### 4. Experimental Analysis

A detailed experimental analysis considering 4 biomasses with different percentage of binders have been carried out. The experimental system comprises downdraft biomass gasifier of inside diameter of 665 mm, 0.25mm thickness and height if about 2110mm. The throat diameter is about 200mm. Air blower with the specification of 220-240V, 500W, 0-16000 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 1cm 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  $\pm 3\% \pm 0.1$  is installed. Total 5 S-type thermocouples with the range of 200°C-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  $\pm 0.1^\circ\text{C}$  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 1180K), weighed pallets gasifying agents are started to supply. For commercialized biomass gasifier another medium of initial heat source can be adopted. After 10-15 minutes 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 1100K 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)[48], 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. As various researchers found this range as optimum range, the range of steam to biomass ratio (SBR) is considered from 0-3, with the value of 0,0.8,1.6,2.4 and 3 [15], [19], [49]. A flow meter is employed to quantify the steam movement. While varying the steam supply, the air supply is kept constant.

After 15-20 minutes, 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.

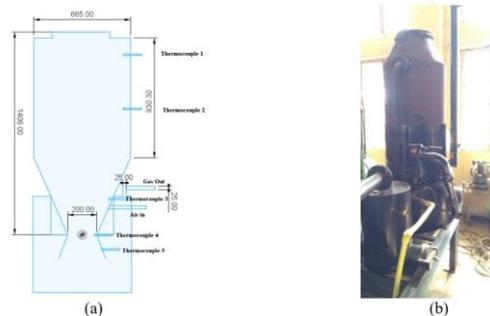


Fig. 4: Biomass gasifier (a) Biomass gasifier design (b) Biomass gasifier set up.

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

$$\left(\frac{A}{F}\right)_{St} = (0.1153 \times C) + (0.3434 \times \left(H - \left(\frac{O}{8}\right)\right) + (0.0434 \times S) \quad (20)$$

$$Q_{PG} = \frac{(b \times CV \text{ of CO}) + (a \times CV \text{ of H}_2) + (e \times CV \text{ of CH}_4)}{100} \quad (21)$$

Table 5. Air flow rate with corresponding equivalence ratio.

	Biomass	(A/F) Stoic	Air flow rate (m <sup>3</sup> /hr)			
			ER=0.2	ER=0.26	ER=0.33	ER=0.39
	Kasai saw dust	6.10	1.22	1.64	2.03	2.43

Without Binder (WEO)	Lemon Grass	4.62	0.85	1.14	1.41	1.69
	Wheat Straw	5.46	1.09	1.47	1.82	2.17
	Pigeon pea seed coat	5.89	1.18	1.58	1.96	2.34
With 5% Binder (WEO)	Kasai saw dust	6.52	1.30	1.75	2.17	2.59
	Lemon Grass	4.74	0.95	1.27	1.58	1.89
	Wheat Straw	5.83	1.17	1.57	1.94	2.32
With 10% Binder (WEO)	Pigeon pea seed coat	6.08	1.22	1.63	2.03	2.42
	Kasai saw dust	6.69	1.34	1.80	2.23	2.66
	Lemon Grass	5.42	1.08	1.46	1.81	2.16
	Wheat Straw	6.22	1.24	1.67	2.07	2.47
	Pigeon pea seed coat	6.52	1.30	1.75	2.17	2.60

## 5. Results and Discussion

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.

### 5.1 Temperature distribution in the gasifier

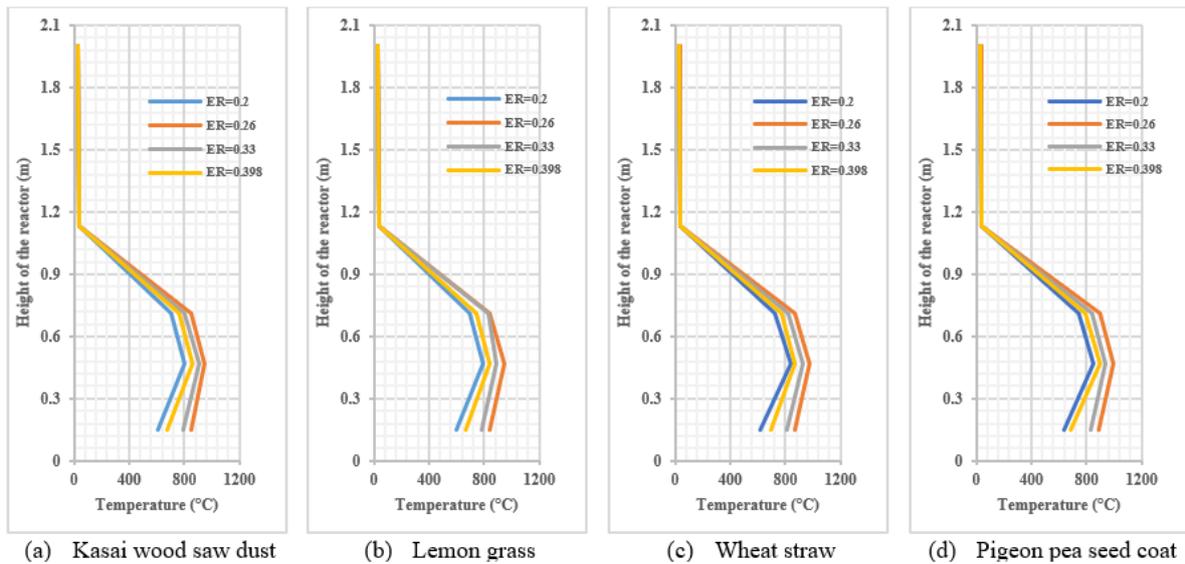


Fig. 5: Temperature profile at different ER for biomasses during gasification process.

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 figure 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 625-825°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  $N_2$  also increases. More  $N_2$  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. [8], [21], [50], [51]

The different temperature profile is obtained for the different feedstock as it based on the composition, density of pellets 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 pellets 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.

## 5.2 Effect of ER on Syngas composition, hydrogen yield and other performance parameters

The equivalence ratio is kept between 0.2-0.4. If the value kept below the range pyrolysis is governing while having more than this combustion is governing. 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/hr 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 0.2-0.398. 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% (figure 6). The model estimate values are somewhat lesser than the experimental data.

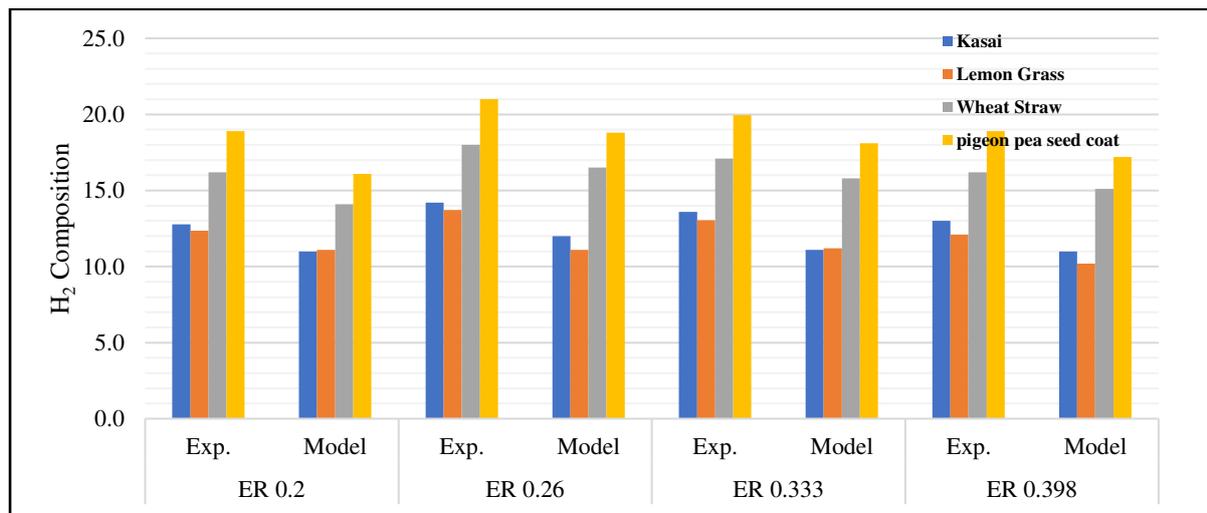
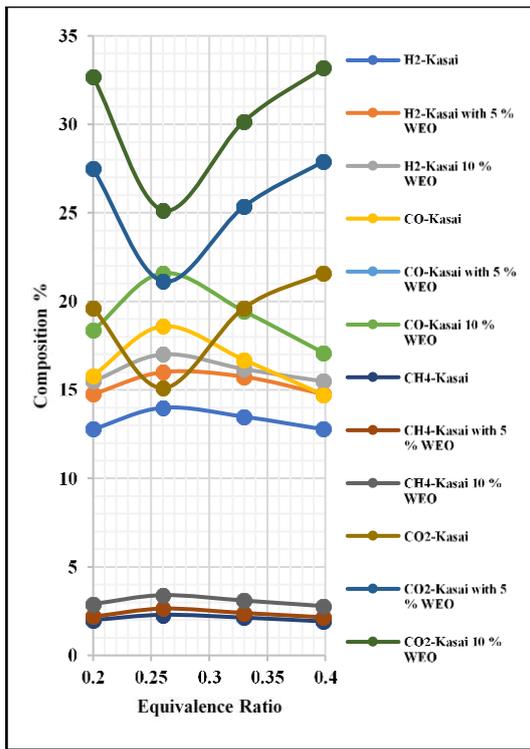
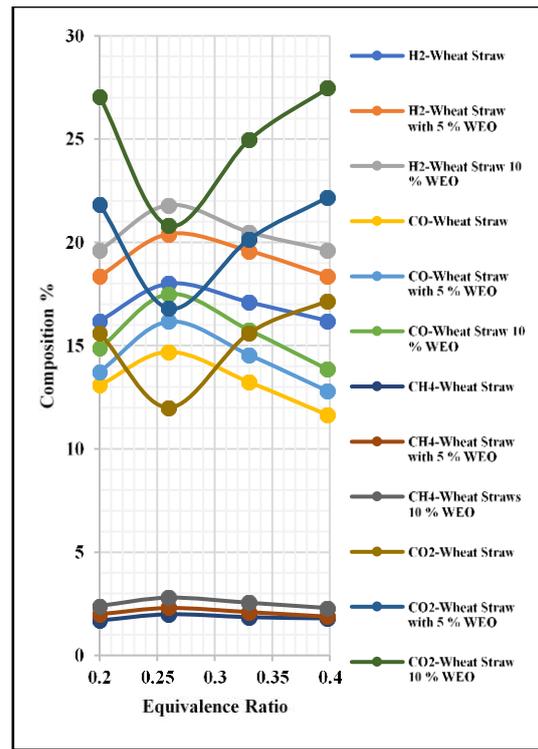


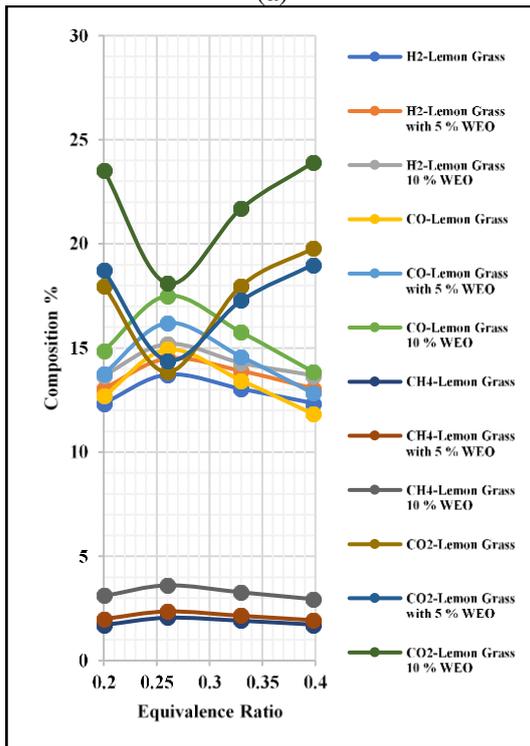
Fig. 6: Experimental and model analysis results for composition of hydrogen of different feedstock without addition of binder.



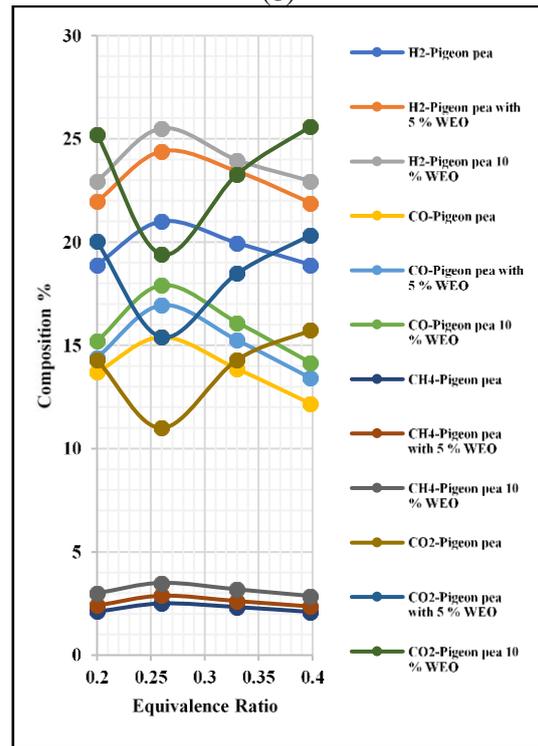
(a)



(b)



(c)



(d)

Figure 7 Product gas composition for different feed stock with varying percentage of binder and different Equivalence Ratio

The Equivalence ratio decides the incomplete combustion for the production of gases like CO. Higher value of ER favours excess oxygen which results in CO<sub>2</sub>. The figure 7 (a-d) shows the composition of CO, CO<sub>2</sub>, H<sub>2</sub> and CH<sub>4</sub> 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 CO<sub>2</sub> increases which shows the conversion of CO into CO<sub>2</sub>. At the maximum value of CO, the CO<sub>2</sub> composition shows minimum value. It can be observed that the percentage composition of CH<sub>4</sub> also increases up to the ER 0.26 and thereafter starts decreasing. It is maximum at 0.26ER for all set of biomasses. The binder increment also shows the increment in CH<sub>4</sub> composition. A similar trend is observed for H<sub>2</sub> composition. Advanced H<sub>2</sub> and CH<sub>4</sub> 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, CO<sub>2</sub>, H<sub>2</sub> and CH<sub>4</sub> 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 O<sub>2</sub>, which enhances the exothermic combustion reaction, which helps the increment of bed temperature. The higher temperature intern supports the endothermic reactions. Reactions R-1, R-4 and R-3 enhance the H<sub>2</sub> and CO compositions in the cost of CO<sub>2</sub> composition. For the higher value of ER, complete combustion of residues enhances which generates CO<sub>2</sub> 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 10.94MJ/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 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/Nm<sup>3</sup> with an ER of 0.26. It perhaps analysed that the increment of waste engine oil also increases the calorific value of product gas.

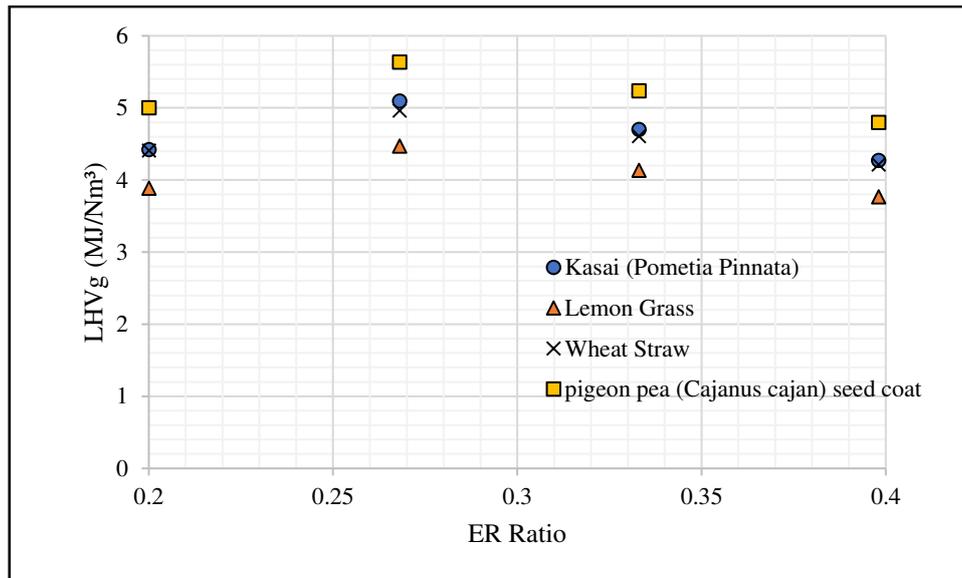


Fig. 8: LHV of Product gas with respect to equivalence ratio without the supply of steam.

It can be observed from the figure 8 that the LHV is maximum for ER 0.26 for all the biomasses. The figure 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/Nm<sup>3</sup> respectively. The LHV depends on the volume fraction of CO, H<sub>2</sub>, and CH<sub>4</sub> 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 Figure 7.

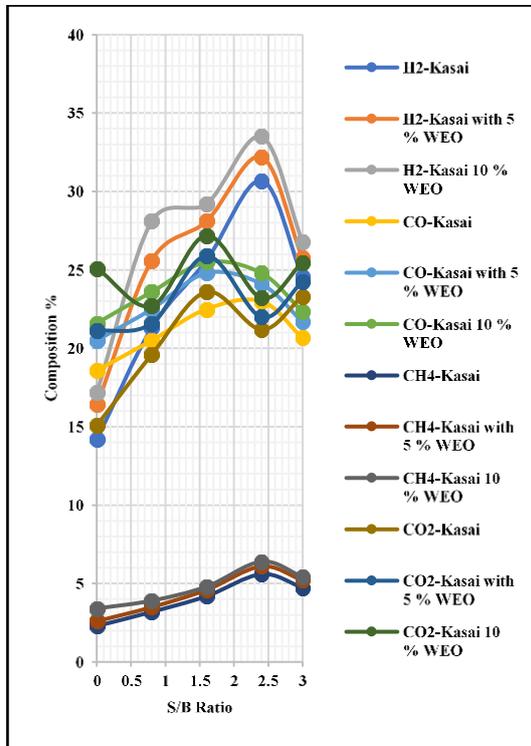
### 5.3 Effect of S/B ratio on Syngas composition, hydrogen yield and other performance parameters

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 H<sub>2</sub>O in the product gas[41]. The higher percentage of steam proceeds to R-4 and R-5 which increases both CO<sub>2</sub> 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 H<sub>2</sub> concentration (14.2–30.7vol.% for Kasai wood dust, 13.7–29.6 vol.% for lemongrass, 21–45.4 vol.% for wheat straw and 18–38.9vol.% 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 15.4–11.01vol.% for pigeon pea seed coat) decreased. The increment in H<sub>2</sub> is because of the increasing rate of the water gas shift reaction at cost of CO.

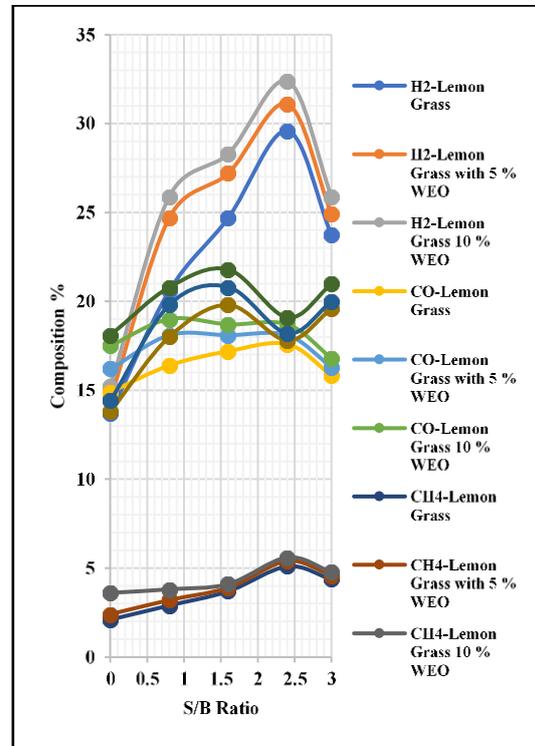
For the composition of CH<sub>4</sub> it is observed that the composition increases not much but continue almost similar to those found with only air. Figure 9 shows the Product gas composition for different feedstock with varying percentage of binder and different S/B Ratio.

It is evident that the addition of binders helps to increase the H<sub>2</sub> and CH<sub>4</sub> yields as compared to without the addition of binders. The H<sub>2</sub> starts increasing as the Steam to Biomass ratio increases. All the set of biomasses shows the higher value of H<sub>2</sub> yields when the S/B ratio is about 2.4 after that it starts

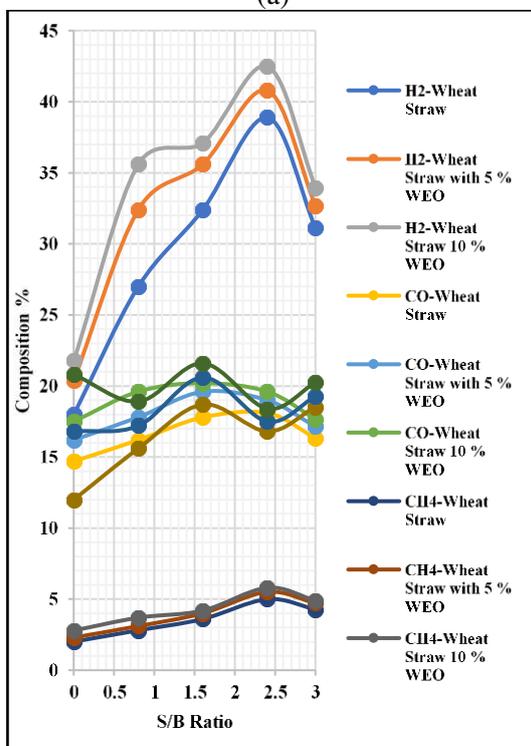
declining. For the set of biomasses with the addition of 5% waste engine oil, H<sub>2</sub> yields increase up to 32.5% for Kasai wood dust, 47.6% for pigeon pea seed coat, 31.1% for lemongrass and 40.8% for wheat straw at 2.4 S/B ratio. Similarly, with the addition of 10% waste engine oil, H<sub>2</sub> 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.



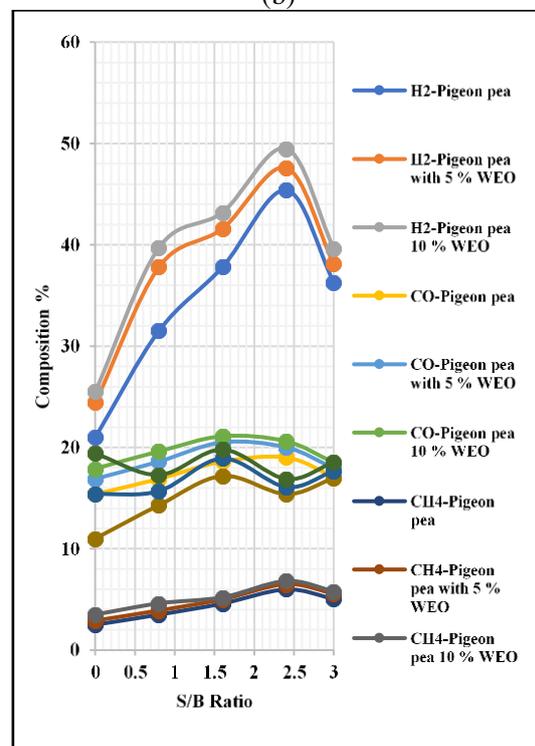
(a)



(b)



(c)



(d)

Fig. 9: Product gas composition for different feed stock with varying percentage of binder and different Steam to Biomass Ratio.

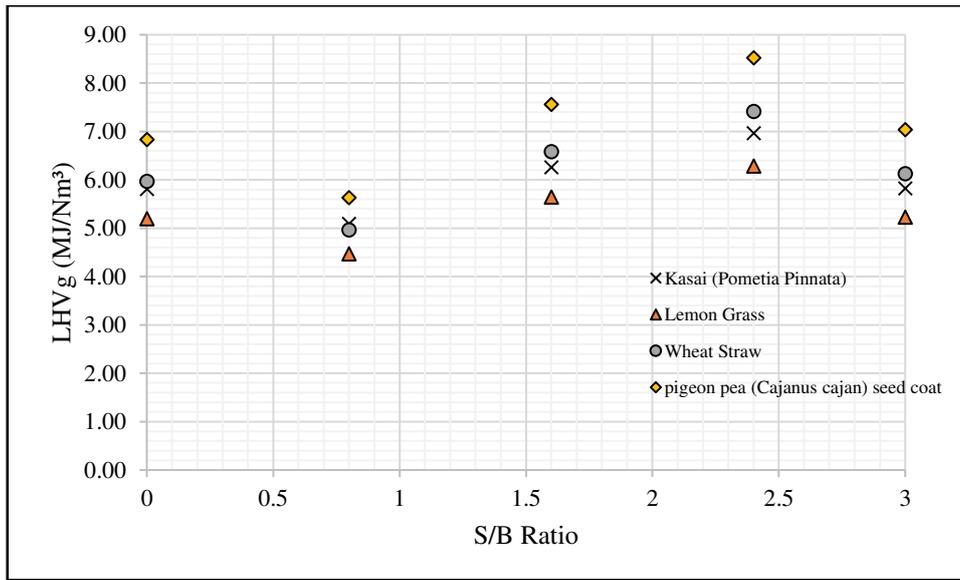


Fig. 10: LHV of Produced gas with respect to Steam to biomass ratio at constant ER 0.24.

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 starts again decreasing depends on important fraction of CO, H<sub>2</sub> and CH<sub>4</sub>. This conclusion also observed in the experimental work carried out by P. Lv et al (2007)[15]. The figure 10 considered the values for biomasses without binders. Based on experimental data, it can be finding out 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<sup>3</sup> for Kasai wood dust, 4.47, 4.85 and 5.59 MJ/Nm<sup>3</sup> for lemon grass, 4.96, 5.57 and 6.12 MJ/Nm<sup>3</sup> for wheat straw and 5.63, 6.41 and 6.93 MJ/Nm<sup>3</sup> 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<sup>3</sup> for Kasai wood dust, 6.28, 6.77 and 7.66 MJ/Nm<sup>3</sup> for lemongrass, 7.42, 7.98 and 8.53 MJ/Nm<sup>3</sup> for wheat straw and 8.53, 9.17 and 9.77 MJ/Nm<sup>3</sup> 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<sub>2</sub> difference with S/B ratio.

## 6. 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 compare to air gasification through thermochemical energy conversion gasification process.
- The H<sub>2</sub> 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 18–38.9vol.% 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 H<sub>2</sub> 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 compare to the biomasses without the addition of the waste engine oil.

## Nomenclature

A	Air
a,b,c,d and e	Coefficients of elements of the product.
AR,	Pre-exponential factor, $\text{k.mol m}^{-3}\text{s}^{-1}$
C	Carbon
Ch <sub>4</sub>	Methane
CO	Carbon Mono Oxide
C <sub>RF</sub>	Char reactivity factor
ER	Equivalence ratio
E <sub>Ri</sub>	Activation energy, $\text{J mol}^{-1}$
F	Fuel
FC	Fixed carbon
H	Hydrogen
hf <sub>g</sub>	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
n <sub>i</sub>	Number of species in mole
n <sub>tot</sub>	Total number of all species in product gas in moles
O	Oxygen
Q <sub>PG</sub>	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
$\Delta G^0$	Standard Gibbs function of formation.
$\Delta H^0$	Heat of formation

## Data availability statement

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.

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