



# Thermodynamic Analysis of Biomass Gasification for Energy Sustainability in Bangladesh and Major Crop Producing Asian Countries

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**Abstract** – Biomass has an important role for energy sustainability issues in tropical countries. In this present study biomass gasification process has been studied using a stoichiometric equilibrium model of biomass gasifier. The gasification process has been considered as a combination of methanation reaction and water gas shift reaction. The reaction rate constants have been considered as an explicit function of gasification temperature. The model has been validated with available experimental results and used to study the effect of equivalence ratio and reaction temperature on the overall gasification process. Three different biomasses specifically rice straw, rice husk and animal manure waste have been considered. The equivalence ratio has been varied from 0.15 to 0.35 for all considered biomass feedstock. The gasification model has been examined for temperatures 1073K and 1173K for all combinations of biomass and equivalence ratio. The mole percentage of different gas specifically hydrogen, carbon monoxide, methane and carbon dioxide have been calculated as a function of the theoretical mole fraction of different gases and equivalence ratio for all the considered biomasses. The cold gas efficiency and lower heating value of the produced gas mixture have been estimated. Finally estimation of energy by biomass gasification has been examined for energy sustainability in major crop-producing Asian nations.

**Keywords** – Crop and animal manure waste, equivalence ratio, gasification, stoichiometric equilibrium, sustainability.

## 1. INTRODUCTION

In the present situation of global economic and environmental demand, it has been observed that the continuous increase in energy demand must be sustainable and compatible with the environmental standards of earth. Renewable and eco-friendly technology is required to reduce the pollution by conventional energy conversion technique. Biomass gasification has been observed as an admirable alternative in this regard. It has also been observed that renewable natural resources like crops, animal products and manure waste have not been utilized in its full capacity for past and present decades in the conventional techniques of energy production. It has been identified as per available data that countries in Asia are capable to recycle their yearly production of crops and animal manure into energy with a greater sustainable impact on their economy and environment. Crops and animal manure waste have been considered with great potential to solve the energy crisis and sustainability issues using gasification technology for a long period of time. The gasification temperature and airflow rate have been identified as major influential parameters for biomass gasification. The effect of these influential parameters on biomass gasification has been studied by several techniques in different literature [1]-[4]. The stoichiometric equilibrium method and minimization of

Gibb's free energy method have been identified as the most effective and efficient technique [5]-[9]. In this present study thermodynamic analysis of biomass gasification process has been carried out using a stoichiometric equilibrium method to predict the performance of the biomass gasifier and to study the role of sustainable energy generation for Bangladesh and other major crop-producing nations in Asia.

## 2. OBJECTIVE AND DESCRIPTION OF STUDY

In the present study biomass gasification process has been studied using a stoichiometric equilibrium model. The model has been developed to study the effect of equivalence ratio and reaction temperature on the overall gasification process. Three different biomasses such as rice straw, rice husk and animal manure waste have been considered. The proximate and ultimate analysis data of these biomasses on a dry basis have been taken from available literature of Tillman *et al.* [10] and Kitani *et al.* [11], are tabulated in Tables 1 and 2.

**Table 1. Ultimate analysis of biomass wt% on dry basis.**

Biomass	C	H	O	N	Ash	HHV (MJ/Kg)
Rice Straw	39.2	5.1	35.8	0.6	19.3	15.21
Rice Husk	38.5	5.7	39.8	0.5	15.5	15.38
AMW	42.7	5.5	31.3	2.4	18.1	17.17

**Table 2. Moisture content of biomass (wt % of dry biomass).**

Biomass	Rice Straw	Rice Husk	AMW
MC	8	10	22

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In the present work, the gasification process has been considered as a combination of methanation reaction and water gas shift reaction. The mass balance of different constituent elements in reactant has been considered with the reaction rate constant to evaluate different gas yields due to gasification. The reaction kinetics has been studied by different literature [12]-[21]. It has been found that the reaction rate constants are the function of Gibb's free energy and reaction temperature. It has also been observed that Gibb's free energy depends on the enthalpy of reactants and products of the reaction at reaction temperature. Therefore, it has been identified that without the use of Gibb's free energy calculation by conventional enthalpy method (Gibb's free energy in terms of enthalpy of reactant and product); it can also be calculated from the temperature of the reaction. In the present model, a simplified reaction rate constant formula has been used to predict product gas composition such as hydrogen, carbon monoxide, methane, carbon dioxide and water vapour. It has been observed that the reaction rate constant has been multiplied by a certain factor to fit the result with experimental data to compensate for the simplification of real and complex gasification processes by a simplified mathematical model. It has also been identified that the process of selection of multiplication factor to the reaction rate constant is not methodical and comprises a trial and error procedure. To avoid the ambiguity of trial and error for the multiplication factor, a thorough study of the gasification process and its influential parameter has been carried out. It has been identified that the different gas yield in the gasification process depends on the equivalence ratio, gasification temperature and steam flow rate. The mole percentages of different gases have been calculated as a function of theoretical mole fraction of corresponding gas and equivalence ratio. The cold gas efficiency (CGE) and lower heating value (LHV) of the produced gas have been calculated from the mole percentage of different gases. Outcome of the estimated performance using the developed model has been used to examine energy sustainability in terms of estimated energy by biomass for countries like Bangladesh, India, China, Thailand, Indonesia, Myanmar, Vietnam and the Philippines. Therefore estimation of their energy by biomass has been studied from available data. It has been found that these countries are the main producer of the crop in Asia according to the Food and Agriculture Organization (FAO) of the United Nations. The data used to get their crop production per year has been taken from FAO statistics about crop production. The data for paddy production per year has been taken from the average of yearly production from 1994 to 2018. On the other hand, animal manure waste has been considered as cattle manure only because it contributes nearly 90% of total animal manure waste production per year. The paddy production rate and animal manure (cattle manure) in million tonnes (Mt) per year have been given in Table 3.

Nguyen Van Hung *et al.* [22] reported straw to grain ratio (SGR) of rice from yearly paddy yield as 4.3:1 by and the same value also was reported by Salman Zafar [23]. On the other hand straw to grain ratio for rice has been reported as 3:1 by R. B. Singh *et al.* [24]. ESCAP (Economic and Social Commission for Asia and the Pacific) and CSAM (Centre for Sustainable Agricultural Mechanization) have reported straw to grain ratio as 1.28:1 in the United Nations report [25].

**Table 3. Paddy and AMW production per year for countries.**

Country	Paddy(Mt/year) 1994-2018 average	AMW (Mt/year) 2017 survey
Bangladesh	41.7	0.8
China	193.1	5.6
India	140.9	7.03
Indonesia	60.4	1.1
Myanmar	24.5	1.18
Philippines	14.9	0.2
Thailand	29.4	0.31
Viet Nam	36.3	0.37

The IRRI (International Rice Research Institute), has reported the grain to husk ratio as 3.5:1 in their Rice Knowledge Bank [26]-[27]. FAO (Food and Agriculture Organization) [28] of the United Nations reported the grain to rice husk ratio (GHR) as 7:3 in their article of grain losses in rice processing. Therefore in the present study for calculation of rice straw and rice husk, the straw to grain ratio and grain to husk ratio have been considered as 3:1 and 4:3, respectively, considering all the losses during rice milling and paddy harvesting process. To study the regional effect on the straw to grain ratio and grain to husk ratio, data of total paddy, milled rice, rice straw and rice husk production have been considered and shown in Table 4.

**Table 4. Paddy, milled rice, rice Straw and rice husk production in million tonnes (Mt) per year for different countries (IRRI statistics 2014).**

Country	Paddy	Milled rice	Rice Straw	Rice Husk
China	206.5	144.56	264.32	61.94
India	157.2	105.48	201.216	51.72
Indonesia	70.84	35.56	90.6752	35.28
Bangladesh	52.32	34.5	66.9696	17.82
Vietnam	44.97	28.16	57.5616	16.81
Thailand	32.62	18.75	41.7536	13.87
Myanmar	26.42	12.6	33.8176	13.82
Philippines	18.96	11.91	24.2688	7.05

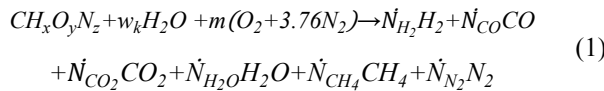
### 3. METHODOLOGY

Biomass gasification is a very complex chemical process and depends on several reaction kinetics and different influential parameters like temperature, pressure, oxygen

content, carbon content, steam flow rate, the ash content of biomass and moisture content of biomass[29]-[32]. It has also been identified that the gasification process can be simulated by addressing the important chemical kinetics of the process on an overall basis. It has been observed that the most popular methods to address the kinetics and the different conservation principles are stoichiometric equilibrium method and minimization of the Gibbs free energy method. In the present work, the stoichiometric equilibrium method has been used.

### 3.1 Development of Mathematical Model

To analyse the main gasification process the gasification equation has been considered as Equation 1;



Where  $w_k, x, y, z, m$  have been calculated from biomass ultimate analysis and from the Equations 2 and 3;

$$w_k = \frac{M_B \times MC}{(1 - MC) \times 18} \quad (2)$$

$$m = \lambda(1 + 0.25x - 0.5y) \quad (3)$$

Here the values of  $\dot{N}_{H_2}, \dot{N}_{CO}, \dot{N}_{CO_2}, \dot{N}_{H_2O}, \dot{N}_{CH_4}, \dot{N}_{N_2}$  have been considered as the unknown parameter.

These values of unknown parameters have been calculated to get the composition of producer gas yield.

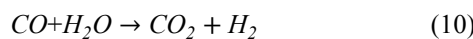
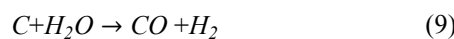
For this purpose, the equations of mass balance for carbon, hydrogen, oxygen and nitrogen have been used along with methanation reaction and water-gas shift reaction, which are given in Equations 4 to 11;

$$\dot{N}_{CO} + \dot{N}_{CO_2} + \dot{N}_{CH_4} = 1 \quad (4)$$

$$2\dot{N}_{H_2} + 2\dot{N}_{H_2O} + 4\dot{N}_{CH_4} = x + 2w_k \quad (5)$$

$$\dot{N}_{CO} + 2\dot{N}_{CO_2} + \dot{N}_{H_2O} = y + w_k + 2m \quad (6)$$

$$2\dot{N}_{N_2} = z + 7.52m \quad (7)$$



Here Equations 8 and 9 have been combined together to form Equation 10 (water-gas shift reaction).

### 3.2 Analysis of Reaction Kinetics

The main reactions in gasification process have been assumed as combination of water-gas shift reaction and methanation reaction represented in Equations 10 and 11. The reaction rate constants of methanation reaction

and water-gas shift reaction have been related to the unknown parameters by Equations 12 and 13;

$$K_{mn} = \frac{\dot{N}_{CH_4}}{(\dot{N}_{H_2})^2} \quad (12)$$

$$K_{wgs} = \frac{\dot{N}_{H_2} \times \dot{N}_{CO_2}}{\dot{N}_{CO} \times \dot{N}_{H_2O}} \quad (13)$$

Through analysis of chemical kinetics, it has been observed that the equilibrium rate constants ( $K_{mn}$  and  $K_{wgs}$ ) are functions of reaction temperature  $T$  and Gibbs free energy ( $\Delta g_{mn}^0, \Delta g_{wgs}^0$ ) of the corresponding reactions. It has also been observed that the Gibbs free energy is a function of reaction temperature. Therefore the reaction rate constants have been calculated as a function of gasification temperature. The functional formula of reaction rate constants (Equations 14 to 17) has been adopted from the simplified reaction rate constant formula of Zainal *et al.* [33].

$$K_{mn} = \exp\left(-\frac{\Delta g_{mn}^0}{RT}\right) \quad (14)$$

$$K_{wgs} = \exp\left(-\frac{\Delta g_{wgs}^0}{RT}\right) \quad (15)$$

$$K_{mn} = \exp\left(\frac{5878}{T} + 1.86 \ln T - 0.27 \times 10^{-3}T - \frac{58200}{T^2} - 18\right) \quad (16)$$

$$K_{wgs} = \exp\left(\frac{7082.842}{T} - 6.567 \ln T + \frac{7.467 \times 10^{-3}}{2}T - \frac{2.167 \times 10^{-6}}{6}T^2 + \frac{0.702 \times 10^{-5}}{2T^2} + 32.541\right) \quad (17)$$

### 3.3 Numerical Method Adopted

The six Equations 4, 5, 6, 7, 12 and 13 have been solved simultaneously to get the Equation 18;

$$A\dot{N}_{H_2}^4 + B\dot{N}_{H_2}^3 + C\dot{N}_{H_2}^2 + D\dot{N}_{H_2} + E = 0 \quad (18)$$

The developed equation (Equation 18) has been found as a fourth degree polynomial of mole fraction of hydrogen. The coefficients of this polynomial have been calculated from Equations 19 to 23;

$$A = 5K_{mn}^2 K_{wgs} \quad (19)$$

$$B = 6K_{mn} K_{wgs} - 6K_{mn} \quad (20)$$

$$C = K_{mn} - 2 + K_{mn} K_{wgs} (2C_2 - 6C_1 - 4) \quad (21)$$

$$D = 4 + 2C_1 - 4C_2 + K_{wgs} (2C_2 - 2C_1 - 4) \quad (22)$$

$$E = K_{wgs}(C_1^2 - 2C_1C_2 + 4C_1) \quad (23)$$

The values of  $K_{mn}$ ,  $K_{wgs}$  have been calculated from Equations 16 and 17 for different temperatures and the values of  $C_1$ ,  $C_2$  have been calculated from Equations 24 and 25;

$$C_1 = x + 2w_k \quad (24)$$

$$C_2 = y + w_k + 2m \quad (25)$$

After getting all the coefficients of Equation 18 it has been solved by the general solution of fourth degree polynomial. With the use of general solution for fourth degree polynomial, the value of mole fraction for hydrogen (the roots of Equation 18) has been calculated from Equations 26 to 33;

$$[\dot{N}_{H_2}]_{1,2} = -\frac{B}{4A} - S \pm \frac{1}{2} \sqrt{-4S^2 - 2P + \frac{Q}{S}} \quad (26)$$

$$[\dot{N}_{H_2}]_{3,4} = -\frac{B}{4A} + S \pm \frac{1}{2} \sqrt{-4S^2 - 2P - \frac{Q}{S}} \quad (27)$$

$$P = \frac{8AC - 3B^2}{8A^2} \quad (28)$$

$$Q = \frac{B^3 - 4ABC + 8A^2D}{8A^3} \quad (29)$$

$$S = \frac{1}{2} \sqrt{-\frac{2}{3}P + \frac{1}{3A} \left( W + \frac{U}{W} \right)} \quad (30)$$

$$W = \sqrt[3]{\frac{V + \sqrt{V^2 - 4U^3}}{2}} \quad (31)$$

$$U = C^2 - 3BD + 12AE \quad (32)$$

$$V = 2C^3 - 9BCD + 27B^2E + 27AD^2 - 72ACE \quad (33)$$

Out of these four different values of mole fraction for hydrogen; the real and mass balance compatible solution has been considered. After getting the values of mole fraction for hydrogen the mole fractions for  $CH_4$ ,  $CO$ ,  $CO_2$  and  $H_2O$  have been calculated from Equations 34 to 38;

$$[\dot{N}_{H_2}]_{th} = \dot{N}_{H_2} \quad (34)$$

$$[\dot{N}_{CH_4}]_{th} = K_{mn}\dot{N}_{H_2}^2 \quad (35)$$

$$[\dot{N}_{CO}]_{th} = \frac{4 - 2C_2 + C_1 - \dot{N}_{H_2} - 5K_{mn}\dot{N}_{H_2}^2}{2} \quad (36)$$

$$[\dot{N}_{CO_2}]_{th} = \frac{2C_2 - 2 - C_1 + \dot{N}_{H_2} + 3K_{mn}\dot{N}_{H_2}^2}{2} \quad (37)$$

$$[\dot{N}_{H_2O}]_{th} = \frac{C_1 - \dot{N}_{H_2} - K_{mn}\dot{N}_{H_2}^2}{2} \quad (38)$$

After all the calculations, it has been identified that the mole fractions of different constituent gases are multiple of their corresponding experimental values, by some factor. It has also been examined that the trend of mole fraction of different gases with respect to the equivalence ratio remains same as that of the experimental result. Therefore, the actual values of different gas yields have been calculated as fraction of theoretical mole fraction of different gas yields. Hence the actual mole fractions of  $H_2$ ,  $CH_4$ ,  $CO$  and  $CO_2$  have been calculated from Equations 39 to 46;

$$[\dot{N}_{H_2}]_{act} = \frac{[\dot{N}_{H_2}]_{th}}{F_{H_2}} \quad (39)$$

$$[\dot{N}_{CH_4}]_{act} = \frac{[\dot{N}_{CH_4}]_{th}}{F_{CH_4}} \quad (40)$$

$$[\dot{N}_{CO}]_{act} = \frac{[\dot{N}_{CO}]_{th}}{F_{CO}} \quad (41)$$

$$[\dot{N}_{CO_2}]_{act} = \frac{[\dot{N}_{CO_2}]_{th}}{F_{CO_2}} \quad (42)$$

$$F_{H_2} = -200\lambda^4 + 1933\lambda^3 - 72\lambda^2 + 11\lambda + 1.9 \quad (43)$$

$$F_{CH_4} = 1791\lambda^4 - 1632\lambda^3 + 501\lambda^2 - 57.4\lambda + 6.2 \quad (44)$$

$$F_{CO} = 1167\lambda^4 - 1467\lambda^3 + 636\lambda^2 - 105\lambda + 7.6 \quad (45)$$

$$F_{CO_2} = 0.1 \quad (46)$$

With the calculated values of mole fractions of all combustible gases ( $H_2$ ,  $CO$  and  $CH_4$ ) the  $LHV_g$  (lower heating value) of the produced gas has been calculated from Equation 47;

$$LHV_g = 10.78 \times \%H_2 + 12.63 \times \%CO + 35.88 \times \%CH_4 \quad (47)$$

[MJ]/Nm<sup>3</sup>]

Next to this the  $LHV_B$  (lower heating value of biomass) has been calculated from ultimate analysis of biomass and Equation 48;



$$LHV_B = HHV_B - h_b \left( \frac{9H + MC}{100} \right) \quad (48)$$

With the values of  $LHV_B$  and  $LHV_g$  the cold gas efficiency of gasification and estimated energy [34] with respect to the yearly biomass (rice straw, rice husk and AMW) production has been calculated from Equations 49 to 53 with mechanical and turbine efficiency 0.806 [35];

$$\eta_{CGE} = \frac{M_g \times LHV_g}{M_B \times LHV_B} \quad (49)$$

$$E_{Rice\ Straw} = \eta_{MT} \eta_{CGE} (0.28 \times P_{Straw} \times LHV_{Straw}) \quad (50)$$

$$E_{Rice\ Husk} = \eta_{MT} \eta_{CGE} (0.28 \times P_{Husk} \times LHV_{Husk}) \quad (51)$$

$$E_{AMW} = \eta_{MT} \eta_{CGE} (0.28 \times P_{AMW} \times LHV_{AMW}) \quad (52)$$

$$E_{Estimated} = E_{Rice\ Straw} + E_{Rice\ Husk} + E_{AMW} \quad (53)$$

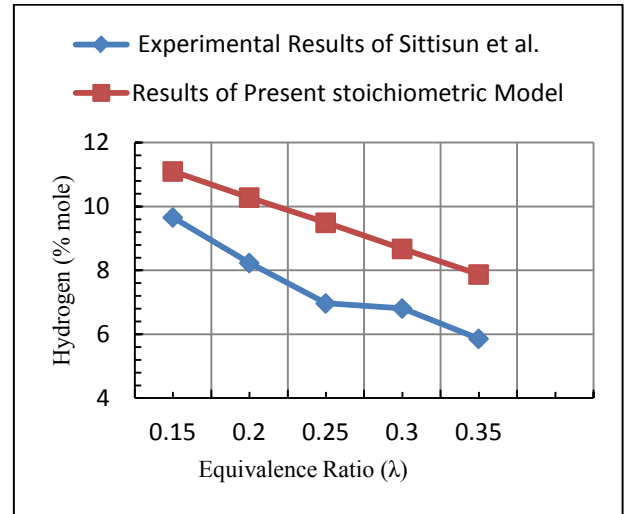
#### 4. MODEL VALIDATION

To ensure the accuracy of the present model, it has been validated with the experimental results of Sittisun *et al.* [36]. For validation, the mole fractions of hydrogen, methane, carbon monoxide with respect to equivalence ratio have been compared between the experimental results and results obtained from the present model. The present study has been carried out for corn-cob biomass and the gasification temperature as 1073K. The moisture content for corn-cob has been considered as zero and the ultimate analysis data of Corn-Cob have been taken from the original reference shown in Table 5.

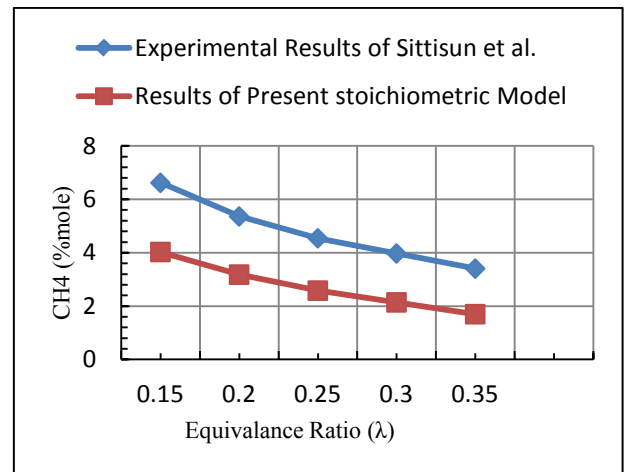
The mole fractions of different gas yield (hydrogen, methane, carbon monoxide) with respect to different equivalence ratio have been given in Figures 1 through 3. Result of lower heating value with respect to different equivalence ratio has been given in Figure 4. After the calculations of mole fractions of different gases the lower heating value ( $LHV$ ) of the produced gas has been calculated with respect to different equivalence ratio and compared with the experimental results. From the obtained results it has been identified that the mole fractions of different constituent gases are well validated with corresponding experimental values. It has also been observed that the trend of mole fraction of different gas with respect to the equivalence ratio remains same as that of the experimental result. The fluctuations have been identified and found very small with respect to the different equivalence ratio of gasification process.

**Table 5. Ultimate analysis of corn-cob wt% on dry basis [36].**

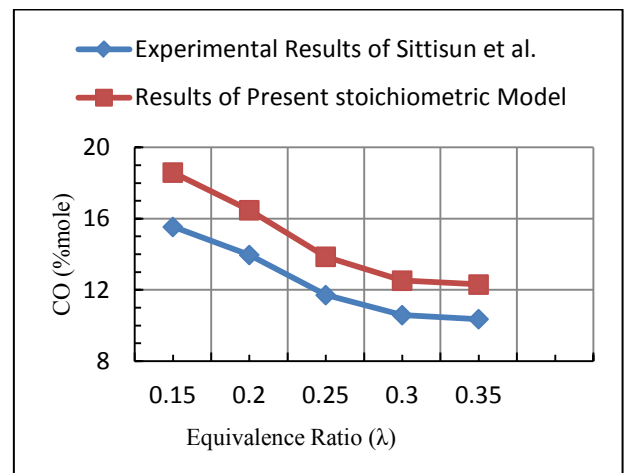
Biomass	C	H	O	N	HHV(MJ/Kg)
Corn-Cob	45.5	6.2	47	1.3	18.7



**Fig. 1. Hydrogen yield with respect to equivalence ratio.**



**Fig. 2. CH4 yield with respect to equivalence ratio.**



**Fig. 3. CO yield with respect to equivalence ratio.**

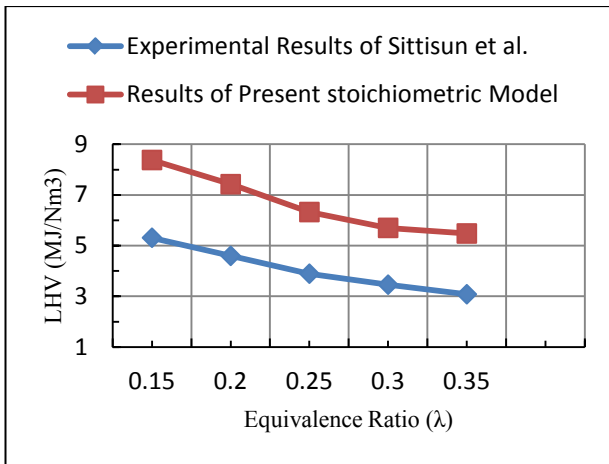


Fig. 4. Lower heating value (LHV) with respect to equivalence ratio.

To understand the exact deviation from experimental result with respect to different equivalence ratio, the root mean square error (RSME) has been calculated for all the produced gases namely hydrogen, methane and carbon monoxide. The calculated RSME for hydrogen gas yield with respect to the corresponding experimental result has been found to be 2.01. In case of methane gas yield, the RSME has been obtained as 2.08 with respect to the corresponding experimental result but for carbon monoxide the RSME has been identified as 2.36 with respect to the corresponding experimental result. In the calculations of lower heating value of produced gas with respect to different equivalence ratio, the RSME has been identified as 2.61 with respect to the corresponding experimental result.

Therefore present model with new kind of nonlinear stoichiometric coefficient for reaction rate constant, with no propagation of error to the next level of calculation has been identified as a well calibrated model.

## 5. RESULTS AND DISCUSSION

Gasification results have been analyzed with respect to equivalence ratio and gasification temperature for three different biomasses namely rice straw, rice husk and animal manure waste (AMW) separately. The results of different gas yield namely hydrogen, methane, carbon dioxide and carbon monoxide have been represented for gasification temperatures 1073K and 1173K along with the variation of equivalence ratio. Lower heating value and cold gas efficiency have also been represented for three different biomasses with the variation of equivalence ratio and temperature. The estimated energy has been represented for top eight crop producing countries of Asia. All the results have been given in the Figures 5 to 22.

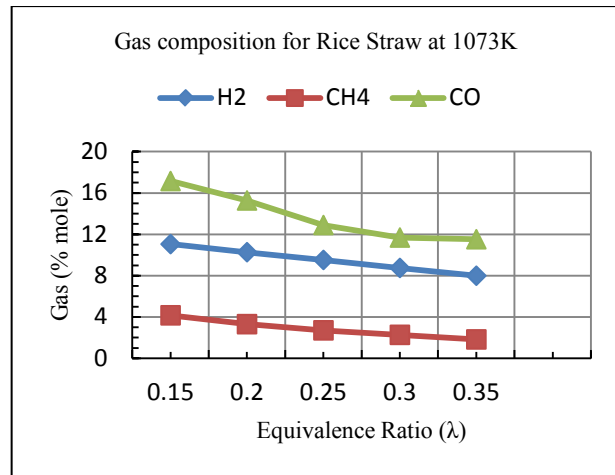


Fig. 5. Composition of different gas yield for rice straw at 1073K with respect to equivalence ratio.

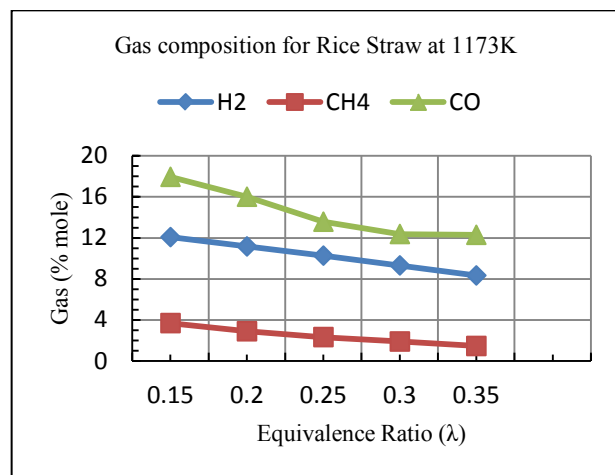
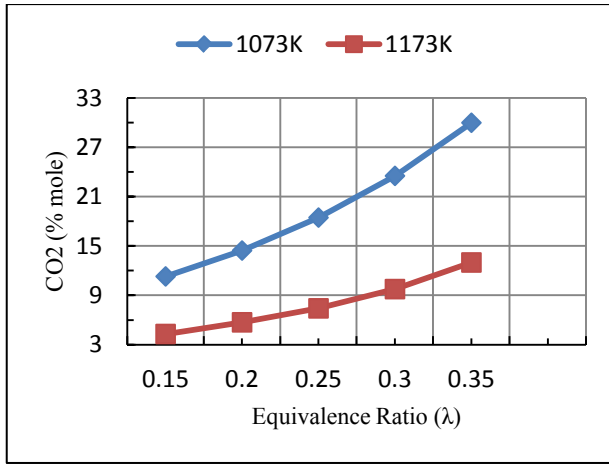


Fig. 6. Composition of different gas yield for rice straw at 1173K with respect to equivalence ratio.

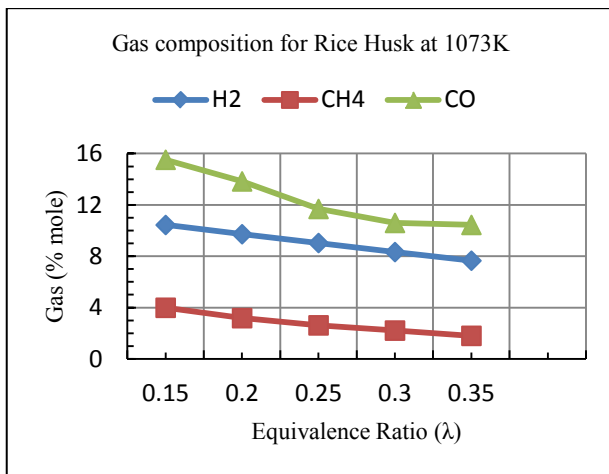
### 5.1 Gasification Results for Rice Straw

In Figure 5 in case of rice straw at 1073K, hydrogen production has been observed to vary from 11 percent to 7.98 percent of produced gas based on mole percent. On the other hand, mole fractions of methane and carbon monoxide have been observed to vary from 4.2 to 1.8 percent and 17.14 to 11.52 percent respectively with the increase of equivalence ratio from 0.15 to 0.35. Similarly at 1173K with rice straw, the mole fraction of hydrogen and methane have been observed to vary from 12.07 to 8.33 and 3.69 to 1.46 percent with the increase of equivalence ratio from 0.15 to 0.35 shown in Figure 6. The mole fraction of carbon monoxide production has been observed to vary from 17.94 to 12.29 percent for variation of equivalence ratio from 0.15 to 0.35 at 1173K shown in Figure 7.

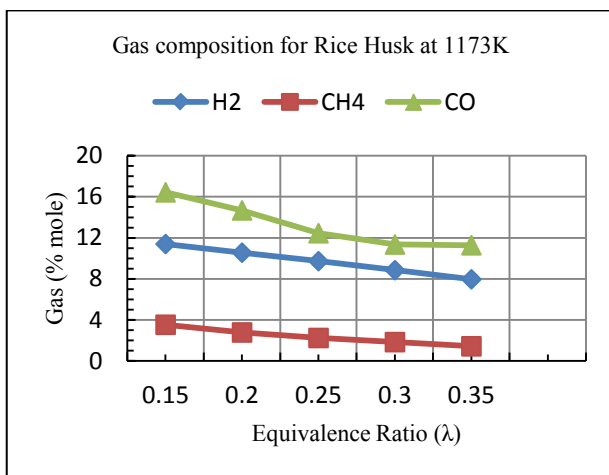


**Fig. 7. Mole percentage of carbon dioxide yield for rice straw at 1073K and 1173K with respect to equivalence ratio.**

**5.2 Gasification Results for Rice Husk**



**Fig. 8. Composition of different gas yield for rice husk at 1073K with respect to equivalence ratio.**



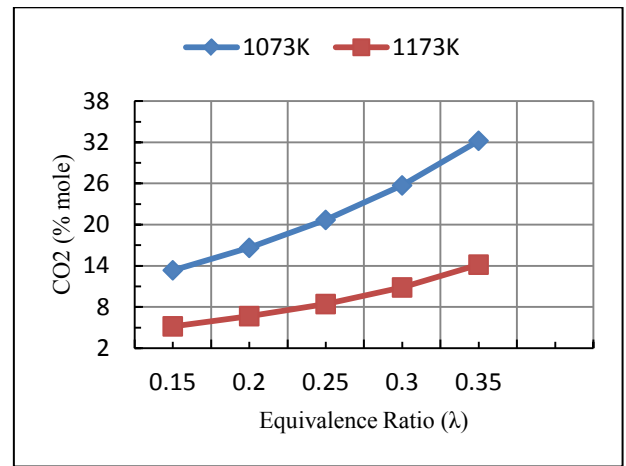
**Fig. 9. Composition of different gas yield for rice husk at 1173K with respect to equivalence ratio.**

Hydrogen production has been observed to vary

from 10.44 percent to 7.65 percent of produced gas based on mole percent for increase of equivalence ratio from 0.15 to 0.35 for rice husk at 1073K shown in Figure 8. Whereas mole fraction of methane and carbon monoxide have been identified to vary from 3.98 to 1.8 and 15.52 to 10.44 percent, respectively.

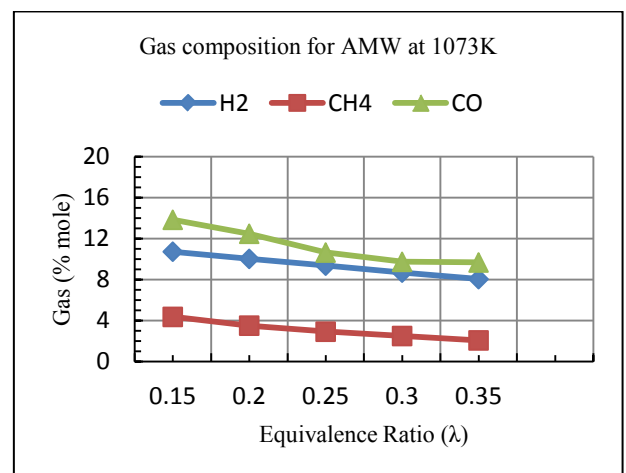
At 1173K the mole fraction of hydrogen and methane have been observed to vary from 11.40 to 7.96 and 3.53 to 1.43 percent with the increase of equivalence ratio from 0.15 to 0.35 for gasification with rice husk shown in Figure 9. At 1173K, the mole fraction of carbon monoxide production has been observed to vary from 16.44 to 11.28 percent for variation of equivalence ratio from 0.15 to 0.35, depicted in Figure 10.

With increase in equivalence ratio, it has been observed from Figures 8 to 10 that the decrease in combustible gas yield for rice husk is almost similar in trends as that of rice straw. But the mole fractions are more for hydrogen and carbon monoxide.



**Fig. 10. Mole percentage of carbon dioxide yield for rice Straw at 1073K and 1173K with respect to equivalence ratio.**

**5.3 Gasification Results for AMW (Animal Manure Waste)**



**Fig. 11. Composition of different gas yield for animal manure waste at 1073K with respect to equivalence ratio.**

Figure 11 shows the results of different gas composition using animal manure waste at 1073K. Hydrogen production has been observed to vary from 10.74 to 8.05 percent of produced gas based on mole percent. Whereas with the increase of equivalence ratio from 0.15 to 0.35 mole fraction of methane and carbon monoxide have been examined to vary from 4.36 to 2.07 percent and 13.85 to 9.68 percent, respectively. For gasification at 1173K with the use of animal manure waste, the mole fraction of hydrogen and methane have been identified to vary from 11.76 to 8.49 and 3.89 to 1.69 percent with the increase of equivalence ratio from 0.15 to 0.35 shown in Figure 12 and mole fraction of carbon monoxide production has been noticed to vary from 14.74 to 10.46 percent for the same variation in equivalence ratio shown in Figure 13.

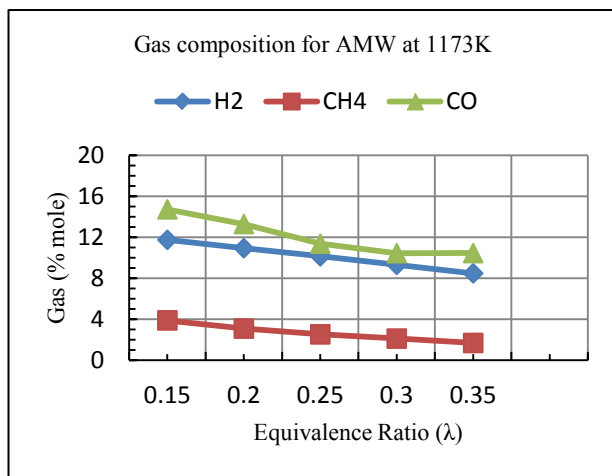


Fig. 12. Composition of different gas yield for animal manure waste at 1173K with respect to equivalence ratio.

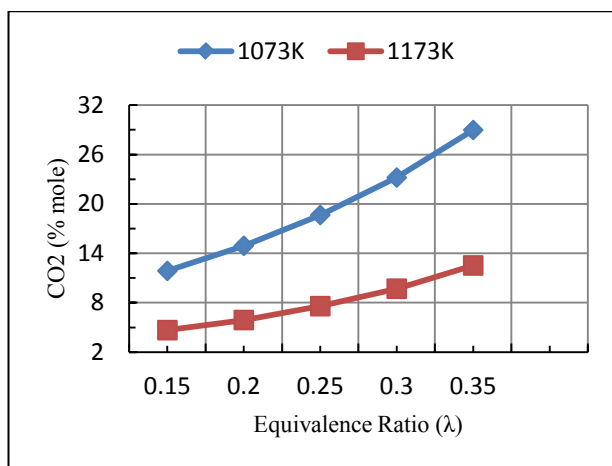


Fig. 13. Mole percentage of carbon dioxide yield for animal manure waste at 1073K and 1173K with respect to equivalence ratio.

#### 5.4 Results for LHV and CGE Calculations

According to the obtained results of mole fractions of hydrogen, methane and carbon monoxide the lower heating value of producer gas has the same decreasing

trend with respect to the equivalence ratio. From the results presented in Figures 14 to 17 it has been observed that the cold gas efficiency is highest for rice straw and lowest for rice husk at almost all equivalence ratio. The lower heating value (LHV) for producer gas has been found with a decreasing trend with respect to the equivalence ratio for all the biomasses.

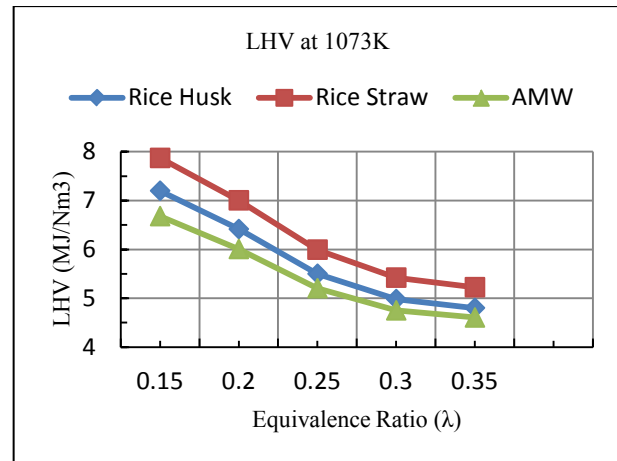


Fig. 14. Lower heating value (LHV) with respect to equivalence ratio at 1073K.

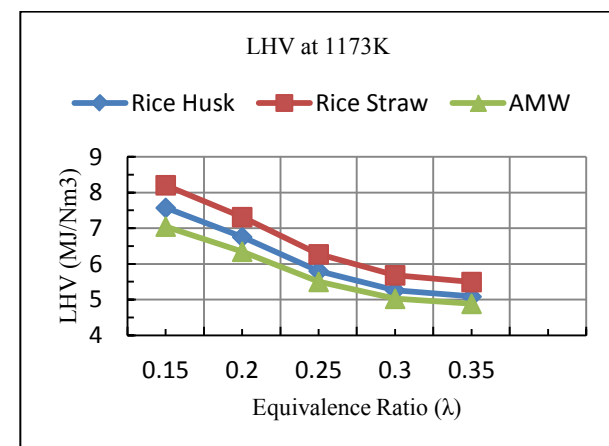


Fig. 15. Lower heating value (LHV) with respect to equivalence ratio at 1173K.

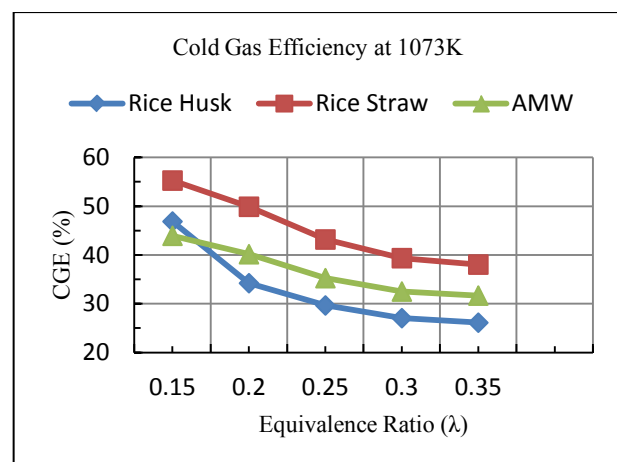


Fig. 16. Cold gas efficiency (CGE) with respect to equivalence ratio at 1073K.



On the other hand the cold gas efficiency has been observed with a similar decreasing trend with respect to the equivalence ratio for all the biomasses namely rice straw, rice husk and AMW at temperatures 1073K and 1173K. The value of lower heating value of producer gas has been examined to vary from 4.5 to 8.5 MJ/Nm<sup>3</sup> whereas the value of cold gas efficiency has been observed to vary from 20 to 70 percent.

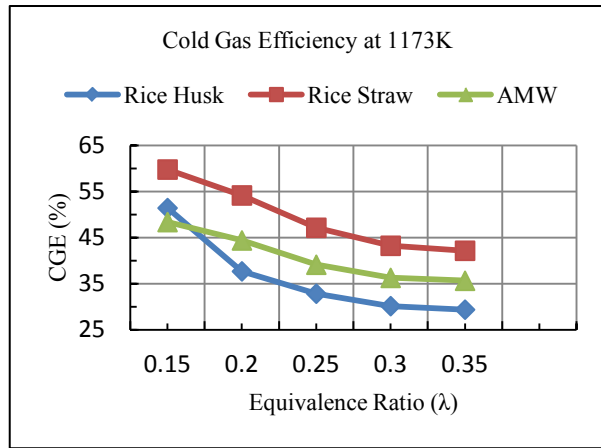


Fig. 17. Cold gas efficiency (CGE) with respect to equivalence ratio at 1173K

### 5.5 Results for Estimated Energy Capacity

With the results of mole fraction, lower heating value, and cold gas efficiency for rice straw, rice husk and animal manure waste, the estimated energy for Bangladesh and top eight crop producing countries in Asia are represented the Figures 18 through 22;

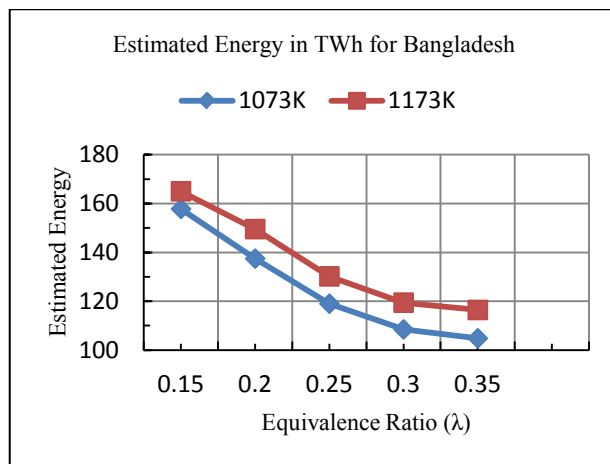


Fig. 18. Estimated energy with respect to equivalence ratio for Bangladesh.

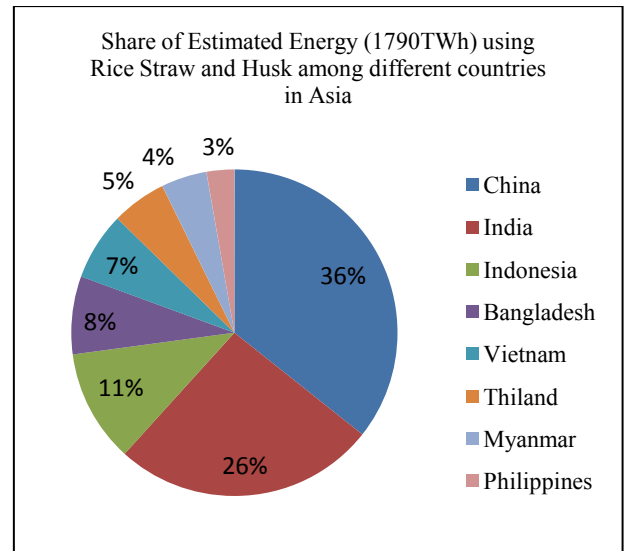


Fig. 19. Share of estimated energy (1790TWh) using rice straw and husk among different countries in Asia.

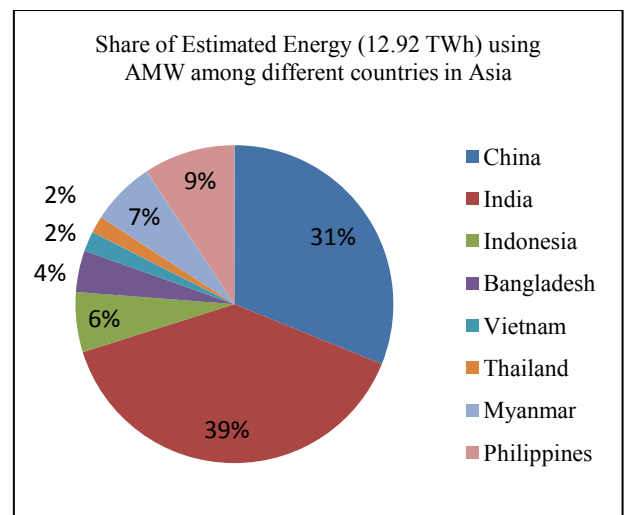


Fig. 20. Share of estimated energy (12.92 TWh) using AMW among different countries in Asia.

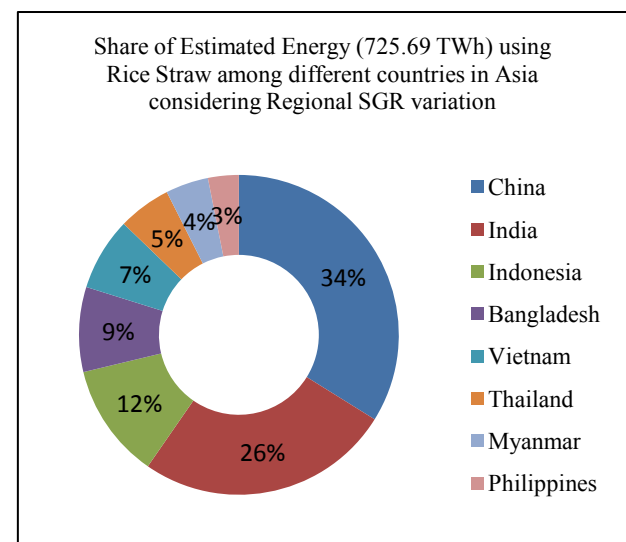


Fig. 21. Share of estimated energy (725.69 TWh) using rice straw among different countries in Asia.

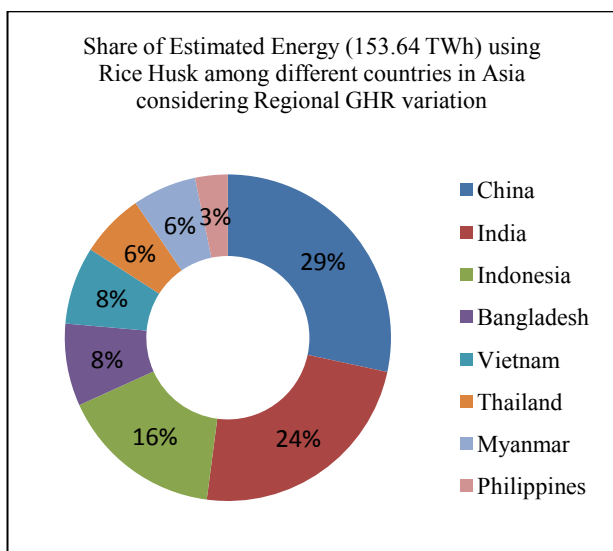


Fig. 22. Share of estimated energy (153.64 TWh) using rice husk among different countries in Asia.

Estimated energy has been observed to vary from 157.78 to 104.83 TWh and from 165 to 116.42 TWh for temperatures 1073K and 1173K, respectively for Bangladesh. With respect to rice straw and rice husk, China and India have been observed to contribute 62 percent of total yearly estimated energy among these eight countries. Bangladesh, Indonesia and Vietnam have been observed with capacity 8, 11 and 7 percent respectively.

For animal manure waste, the capacity of China and India has been observed to be 70 percent of total yearly estimated energy among these eight countries. Whereas the Philippines and Myanmar has been observed to share 9 percent and 7 percent, respectively.

## 6. CONCLUSION

Present study shows that the cold gas efficiency is more for rice straw and animal manure waste for all equivalence ratios and temperatures. The amount of hydrogen, methane and carbon monoxide is more with the rise in temperature. It has also been concluded that the present model have the potential to estimate the energy of different biomasses for different countries with different qualities of paddy yield. It has been realized that the model has successfully calculated the producer gas yield for variation of equivalence ratio and temperature. The estimated energy has been identified to satisfy considerable amount of energy demand in Bangladesh (nearly 165 TWh). It has been inferred that Bangladesh and Indonesia has a great potential of development in the renewable energy sector using biomass specially rice straw and rice husk nearly 7-8 percent of total. On the other hand, it has been derived that in terms of estimated energy from animal manure waste, the Philippines, Myanmar and Indonesia has great opportunity after China and India. On an overall perspective it has been concluded that the developed

gasification model is very useful tool to predict the producer gas yield with a good accuracy and the Asian crop producing countries have a great potential to manage the sustainability crisis in environment and energy demand.

## ACKNOWLEDGEMENT

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## NOMENCLATURE

$x$	Hydrogen to carbon mole ratio in dry biomass
$y$	Oxygen to carbon mole ratio in dry biomass
$z$	Nitrogen to carbon mole ratio in dry biomass
$w_k$	Number of water molecule in dry biomass
$m$	Number of oxygen molecule
$\lambda$	Equivalence ratio
$F_{H_2}$	Theoretical to actual mole fraction ratio for $H_2$
$F_{CH_4}$	Theoretical to actual mole fraction ratio for $CH_4$
$F_{CO}$	Theoretical to actual mole fraction ratio for CO
$F_{CO_2}$	Theoretical to actual mole fraction ratio for $CO_2$
$K_{mn}$	Reaction rate constant of methanation reaction
$K_{wgs}$	Reaction rate constant of water gas shift reaction
$\Delta g_{mn}^0$	Gibb's free energy for methanation reaction
$\Delta g_{wgs}^0$	Gibbs free energy for water gas shift reaction
$H_2$	Hydrogen gas
CO	Carbon monoxide gas
$CH_4$	Methane gas
$CO_2$	Carbon dioxide gas
AMW	Animal manure waste
$M_B$	Mass of dry biomass
MC	Moisture content
$\dot{N}_{H_2}$	Stoichiometric mole fraction of $H_2$
$\dot{N}_{CO_2}$	Stoichiometric mole fraction of $CO_2$
$\dot{N}_{H_2O}$	Stoichiometric mole fraction of $H_2O$
$\dot{N}_{CH_4}$	Stoichiometric mole fraction of $CH_4$
$\dot{N}_{CO}$	Stoichiometric mole fraction of CO
$\dot{N}_{N_2}$	Stoichiometric mole fraction of $N_2$ gas
$R$	Universal gas constant
$T$	Gasification temperature

$[\dot{N}_{H_2}]_{act}$	Actual mole fraction of H <sub>2</sub>
$[\dot{N}_{CH_4}]_{act}$	Actual mole fraction of CH <sub>4</sub>
$[\dot{N}_{CO}]_{act}$	Actual mole fraction of CO
$[\dot{N}_{CO_2}]_{act}$	Actual mole fraction of CO <sub>2</sub>
$[\dot{N}_{H_2}]_{th}$	Theoretical mole fraction of H <sub>2</sub>
$[\dot{N}_{CH_4}]_{th}$	Theoretical mole fraction of CH <sub>4</sub>
$[\dot{N}_{CO}]_{th}$	Theoretical mole fraction of CO
$[\dot{N}_{CO_2}]_{th}$	Theoretical mole fraction of CO <sub>2</sub>
$LHV_B$	Lower heating value of biomass
$HHV_B$	Higher heating value of biomass
$LHV_g$	Lower heating value of producer gas
CGE	Cold gas gasification efficiency
RSME	Root mean square error
$P_{Straw}$	mass of biomass feedstock from rice straw
$P_{Husk}$	mass of biomass feedstock from rice husk
$P_{AMW}$	Mass of biomass feedstock from AMW
$h_b$	Latent heat of vaporisation for water
$\eta_{MT}$	Mechanical and turbine efficiency combined
$\eta_{CGE}$	Cold gas gasification efficiency
$E_{Estimated}$	Total Estimated energy in TWh
$E_{Rice\ Straw}$	Estimated energy in TWh by Rice Straw
$E_{Rice\ Husk}$	Estimated energy in TWh by Rice Husk
$E_{AMW}$	Estimated energy in TWh by animal manure

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