Bioenergy Potential of Three Fast-Growing Trees: A Pilot Gasification Study for Thermal Applications

Abstract

This study was conducted duringMarch-October, 2023 at Forest College and Research Institute, Mettupalayam - 641301 which investigated the gasification potential of three fast-growing, short-rotation species (*Khaya senegalensis*- KS 01, *Mitragynaparvifolia*- MP 01, and *Terminalia bellirica*- FCRITB 13) for renewable energy generation. All three species were found to have favorable characteristics for a potential bioenergy plant in the analysis. A downdraft gasifier was used to convert the biomass into syn-gas, and the calorific value, thermal conversion efficiency, and elemental composition were analyzed. The results showed that Khaya senegalensis- KS 01 had the highest syn-gas composition (CO: 30.15%, H_2: 13.13%, N_2: 48.82%, CH_4: 1.71%), calorific value (6.04 MJ Nm3^{-1}), and thermal conversion efficiency (59.92%). The elemental composition analysis revealed that Mitragynaparvifolia- MP 01 had the highest carbon content (49.33%), while Khaya senegalensis- KS 01 had the highest hydrogen content (5.94%). These findings suggest that Khaya senegalensis- KS 01 is a promising candidate for biomass gasification due to its high syn-gas yield and thermal conversion efficiency.

Keywords: Biomass, Syn-gas, Calorific value, Renewable energy, gasifier

Introduction

The need for energy resources to meet growing demand Human energy consumption is increasing. However, the energy Sources that we currently depend on, such as oil, coal, and natural gas are limited. Therefore there is growth The focus is on creating renewable fuel production systems [1].Biomass is converted into energy using diverse technologies like thermal conversion techniques (combustion, pyrolysis, hydrogen thermal liquefication and biomass gasification process), bioconversion (fermentation and anaerobic digestion) and chemical conversion (transesterification, hydro-processing technologies). The production of high value-added byproducts coupled with renewable energy generation is an integrated bio refinery approach [2]. Considering, the current need and the demand for renewable energy generation it has been planned to support biomass-based gasification technology due to its significance towards carbon benefits. The gasification is a complex thermochemical process and the extended version of the pyrolysis that produces combustible gases [3]. Gasification involves two steps: the first step is conversion of biomass to syn-gas, second step involves a low-pressure gas separation unit to extract pure hydrogen. During this process of conversion over 20% of biomass is converted into biochar, which on application to farmland enhances soil carbon and hence pronounced as a carbon negative project[4]. However, this technologies demand screening of species amenable for its application for biomass power generation through research and development. The present work is an attempt to determine the elemental composition (ultimate analysis) and properties of syngas from three fast-growing tree species using a small downdraft biomass gasifier.

Materials and Methods

The present study was conducted during March-October, 2023. Three fast growing, short rotation species viz., *Khaya senegalensis*- KS 01,*Mitragynaparvifolia*- MP 01, and *Terminalia bellirica*- FCRITB 13 were selected as materials for this study.

By partially oxidizing a solid fuel at a high temperature, biomass gasification is an endothermic thermal conversion process that transforms solid fuels into gaseous energy carriers. The oxidizing agent is a finite amount of oxygen, air, steam, or a mixture of these. The product gas, also known as producer gas, is composed of different pollutants, including small char particles, ash, tars, higher hydrocarbons, and oil, as well as carbon monoxide, carbon dioxide, hydrogen, methane, water, and nitrogen (when air is used as an oxidant). This gas can be used in turbine operation and internal combustion engines or for thermal energy, such as in boilers and furnaces. The type of fuel utilized and whether the gasifier is stationary or movable affect the design. According to a recent survey of gasifier manufacturers, the majority of commercially available gasifiers (75%) are downdraft models, followed by fluid beds (20%), updraft models (2%) and other varieties (2%).

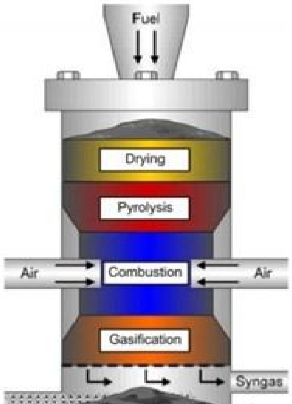

Figure 1: Schematic diagram of downdraft fixed bed gasifier [5]

Carbonaceous materials can be gasified in order to create combustible or fuel gas. The phases of lignite particle gasification in a downdraft gasifier are as follows: A gasifier goes through the four separate procedures listed below (Figure 1):

1. Drying
2. Pyrolysis
3. Some gases, fumes, and char can be partially burned.
4. Gasification of product breakdown or reduction

During the gasification process, complex reactions take place, as shown below [6].

Combustion reactions, $C+½O_2=CO-111\ MJ\ kmol^{-1}$ (1)

$CO+½O_2=CO_2-283\ MJ\ kmol^{-1}$ (2)

$H2+½O_2=H_2O\ -242\ MJ\ kmol^{-1}$ (3)

Boudouard reaction,

$C+CO_2\leftrightarrow 2CO+172\ MJ\ kmol^{-1}$ (4)

Water gas reaction,

$C+H_2O\leftrightarrow CO+H_2+131\ MJ\ kmol^{-1}$ (5)

Methanation reaction,

$C+2H_2\leftrightarrow CH_4-75\ MJ\ kmol^{-1}$ (6)

Water gas shift/CO shift reaction,

$CO+H_2O\leftrightarrow CO_2+H_2-41\ MJ\ kmol^{-1}$ (7)

Steam methane reforming reaction,

$CH_4+H_2O\leftrightarrow CO+3H_2+206\text{ MJ kmol}^{-1}$ (8)

The combustion reactions, Boudouard reaction, water gas reaction, and methanation reaction are all included in coal gasification. The water gas shift (Equation 7) is produced if the Boudouard reaction (Equation 4) is subtracted from the water gas reaction (Equation 5), taking into account the mole and heat effect, and the steam methane reforming reaction (Equation 8) is produced if the methanation reaction (Equation 6) is subtracted from the water gas reaction (Equation 5). Thus, the water gas shift reaction (Equation 7) and steam methane reforming reaction (Equation 8) are implicit in the Boudouard reaction (Equation 4), water gas reaction (Equation 5), and methanation reaction (Equation 6) [6].

Exothermic reactions 4.1 to 4.3 produce practically all of the heat needed to dry the fuel and power reactions 4.4 through 4.6. These reactions almost entirely consume oxygen. These processes don't significantly influence the composition of an equilibrium syn-gas [6]. The principal gasification reactions, which change the composition of the gas, are 4 to 6.

The Boudouard reaction (also known as the char-carbon dioxide reaction), which is substantially slower than the char-oxygen reaction (Equation 1), is what produces carbon monoxide (CO). The primary gasification reaction is reaction 5, which is slightly quicker than Boudouard reaction (Equation 4) [7]. Reaction 5 is the water gas reaction. High temperature enhances the water gas reaction, which yields CO and H_2. With the exception of high-pressure environments, the char-hydrogen reaction produces methane and is the slowest reaction.

Thermochemical interactions between the fuel and the gasification agent result in the production of syn-gas, also known as producer gas, product gas, synthetic gas, or synthesis gas. CO, H_2, N_2, CO_2, and a few hydrocarbons (CH_4, C_2H_4, C_2H_6, etc.) make up the majority of the syn-gas. Tars, NH_3, and extremely minute levels of H_2S may also be present [8].

Gasification and syn-gas composition

A 1 kg capacity down draft gasifier was used to check the gasification potential of the screened clones. Wood chips of 5–10cm length and 5–7cm wide was fed in the gasifier. The gasifier had a blower attached to the unit to induce the oxygen flow for better burning of the wood chips. Finally, the syn-gas released was trapped by a gas bladder and further tested in a gas monitoring system for its composition.

Calorific value of syn-gas

According to a predetermined formula, the calorific value of syn-gas was determined (Wang, 2013). Since only H_2, CO, and CH_4 are combustible, the calorific value of the syn-gas is determined by the higher heating values of these gases[9].

$$\Delta H = (12.76\ \mathrm{MJ\ m^{3-1}} \times H_2\%) + (12.63\ \mathrm{MJ\ m^{3-1}} \times CO\ \%) + (39.76\ \mathrm{MJ\ m^{3-1}} \times CH_4\%)$$

Where,

Standard HHV for $H_2 = 12.76\mathrm{MJ\ m^{3-1}}$,

$CO = 12.63\mathrm{MJ\ m^{3-1}}$,

$CH_4 = 39.76\mathrm{MJ\ m^{3-1}}$

Thermal conversion efficiency of syn-gas

The Rajvanshi (1986) equation can be used to determine the thermal conversion efficiency of gasification. The calorific value of the gas ($\Delta Hgas$), the calorific value of the biomass ($\Delta Hbiomass$) and the volume of syn-gas produced from one kilogram of biomass (V) can all be used to compute the thermal conversion efficiency of gasification. A fixed $2m^3$ volume may be created from 1kg of biomass [10].

$$\eta = \frac{\Delta Hgas\ (kJm^{-3}) \times V(m^3)}{\Delta Hbiomass\ (kJkg^{-1}) \times 1(kg)} \times 100$$

Elemental composition analysis

Utilizing a carbon, hydrogen, nitrogen, and sulfur CHNS/O Analyzer (2400 Series II - PerkinElmer), wood powder was put through to a final examination. A powdered sample of the biomass was added to a combustion reactor for the final analysis, starting a highly exothermic reaction that reached a temperature of almost 1,800°C. The combustion products that resulted were then moved about the reactor. The extra oxygen was kept intact while nitrogen oxides and sulfur trioxides were changed into elemental nitrogen and sulfur dioxide. After that, a gas chromatographic column is used to separate the gas mixture. The chromatographic column's gases were extracted, and they were then sent to a thermal conductivity detector, which produced electrical signals. To ascertain the CHNS content of the material, these signals are analyzed.

The biomass sample was weighed, put in a silver container, and kept in an auto sampler before the oxygen content was determined. The sample was quickly pyrolyzed in the reactor after which the end products were passed through an adsorption filter that contained halogenated chemicals. After that, chromatographic columns were used to extract carbon monoxide from the other gases in the gaseous mixture. To calculate the sample's oxygen % (O), the leftover gaseous mixture was once more fed into the thermal conductivity detector [11].

Results and Discussion

Table 1. Syn-gas composition of three screened species for gasification (%)

Species	**CO**	**CO_2**	**CH_4**	**H_2**	**N_2**
Mitragynaparvifolia-MP 01	25.71 ± 0.91^{b}	**11.71 ± 0.09^{a}**	1.62 ± 0.06^{b}	12.52 ± 0.19^{c}	46.44 ± 0.34^{c}
Khaya senegalensis-KS 01	**30.15 ± 0.76^{a}**	10.95 ± 0.09^{c}	**1.71 ± 0.02^{a}**	**13.13 ± 0.10^{a}**	**48.82 ± 0.52^{a}**
Terminalia bellirica-FCRITB 01	25.10 ± 0.43^{c}	11.45 ± 0.07^{b}	1.40 ± 0.06^{c}	12.72 ± 0.09^{b}	47.50 ± 0.64^{b}
Mean	26.99	11.40	1.58	12.80	47.59
P value	$P< 0.001$	$P< 0.001$	$P< 0.001$	$P< 0.001$	$P< 0.001$

Syn-gas composition

The nature of biomass material has a significant impact on the relative composition of the component gases produced by gasification (CO, H_2, CH_4, and CO_2) and the energy content of the syn-gas [12, 13]. In the current study, the highest carbon monoxide, hydrogen, nitrogen and methane content was reported in *Khayasenegalensis*- KS 01 CO (30.15%), H_2 (13.13%), N_2 (48.82%) and CH_4 (1.71%), whereas, the highest CO_2 (11.71%) content was recorded in *Mitragyanaparvifolia*- MP 01(Table 1). Nwokolo et al. [14] identified comparable results for Eucalyptus wood chips, with syn-gas makeup varying between 22.30% and 22.50% for hydrogen, 22.30% to 24.30% for carbon monoxide, 1.90% to 2.10% for methane, 9.80% to 10.70% for carbon dioxide, and 41.5% to 42.90% for nitrogen. Atnaw et al. and Bridgwater[15, 16] both reported equivalent findings of syn-gas in downdraft gasifier. Di Blasi [17] andWang & Kinoshita [18] also recorded similar results for CO_2, CO, CH_4, H_2 and N_2 composition. Gai&Dong[19]recorded syn-gas composition of H_2 (8.23%), CO (13.55%), CO_2 (20.37%), CH_4 (1.84%) and N_2 (51.15%) in non woody biomass.

Table 2. Syn-gas properties

Species	**Gross Calorific value (MJ Nm^{-3})**	**Thermal conversion efficiency**
Mitragynaparvifolia- MP 01	5.46 ± 0.08^{b}	57.37 ± 0.19^{b}
Khaya senegalensis- KS 01	**6.04 ± 0.06^{a}**	**59.92 ± 0.94^{a}**
Terminalia bellirica- FCRITB 01	5.35 ± 0.05^{c}	50.10 ± 0.65^{c}
Mean	5.62	55.80
P value	$P< 0.001$	$P< 0.001$

Syn-gas properties

Calorific value of syn-gas (MJ Nm$^{3-1}$).

The calorific value of syn-gas (synthesis gas) can vary depending on its composition, which, in turn, depends on the feedstock and the gasification or synthesis process used. Syn-gas typically consists primarily of hydrogen (H_2) and carbon monoxide (CO), along with smaller amounts of other gases such as methane (CH_4) and carbon dioxide (CO_2). Several factors such as the feedstock used, gasification process, temperature, pressure, agent, catalysts, gas cleanup, feedstock re-processing and feedstock blending all influence the calorific value of a syn-gas.

In the current study, the highest calorific value of the syn-gas composition was reported in the screened species *Khaya senegalensis*- KS 01 (6.04 MJ Nm$^{3-1}$), followed by *Mitragynaparvifolia*- MP 01 (5.46 MJ Nm$^{3-1}$) and the lowest value was reported in *Terminalia bellirica*- FCRITB 13 (5.35 MJ Nm$^{3-1}$) (Table 2). Sheth& Babu [20] in Dalbergia wood; Zainalet al. [21];Dogru et al. [22] and Atnaw et al. [15]in another woody biomass have found similar results. Also, Bridgwater[16] reported the calorific value of woody biomass in down draft air blown gasifier was 5.7 MJ Nm$^{3-1}$.

Thermal conversion efficiency (%)

Thermal conversion efficiency is a crucial indicator of the fuel's energy content and a key element in determining more affordable biomass sources for gasification [10]. In the current research, the highest thermal conversion efficiency of gas was recorded in the screened species *Khaya senegalensis*- KS 01 (59.92%), followed by *Mitragynaparvifolia*- MP 01 (57.37%) and *Terminalia bellirica*- FCRITB 13 (50.10%) (Table 2). The findings parallel to the results of Islamova&Vachagina[23], who observed that that thermal conversion efficiency ranged from 40.4 to 96.7% for woody biomass. Umeki et al. [24] also recorded the thermal efficiency range of woody biomass to range from 49.2% to 60.4% after gasification. As reported by Sharma et al. [25], in *Lanatana camara* and Goswami & Das [11] in *Morus rubra* species had comparable thermal conversion efficiency.

Table 3. Elemental composition of the three screened species for gasification (%)

Species	**C**	**H**	**O**	**N**
Mitragynaparvifolia- MP 01	**49.33±0.02**^{a}	5.90±0.01^{a}	43.95±0.02^{b}	0.80±0.01^{c}
Khaya senegalensis- KS 01	48.77±0.02^{b}	**5.94±0.01**^{b}	**44.11±0.05**^{a}	1.16±0.04^{b}
Terminalia bellirica- FCRITB 01	48.34±0.18^{c}	5.92±0.01^{ab}	44.07±0.03^{ab}	**1.52±0.04**^{a}
Mean	48.81	5.92	44.04	1.16
P value	P< 0.001	P< 0.001	P< 0.001	P< 0.001

Elemental composition of the woody biomass

A crucial evaluation that aids in determining the required air-to-fuel ratio for effective combustion is called ultimate analysis. It also contributes to the evaluation of the fuel's potential to cause pollution [26]. Carbon, hydrogen, and lignin are the main substances in charge of producing heat. The heating capability of fuelwood types with low levels of nitrogen, sulphur, and extractive compounds is directly influenced by these constituents [27].

Carbon-carbon bonds have more energy than carbon-hydrogen and carbon-oxygen bonds in any biofuel. Additionally, biomass fuels with higher levels of oxygen and hydrogen have lower energy values [28][29].

The highest Carbon content was recorded in *Mitragynaparvifolia*- MP 01 (49.33%), whereas, the highest oxygen (44.11%), hydrogen (5.94%) was recorded in *Khaya senegalensis*- KS 01and the highest nitrogen content was recorded in *Terminalia bellirica*- FCRITB 13 (1.52%) as shown in Table 3. The results are on par with Sharma *et al.*[25], who carried out ultimate analysis in *Dalbergia sissoo*. The current observations were also in line with those of Baqir et al.[30] who conducted an ultimate analysis on twelve different species of wood and recorded the amounts of C (40.80%), O (46.06%), H (4.72 to 6.73%) and N (0.02 to 1.39%) respectively. Additionally, Dai et al. [31] discovered that the ideal ranges for carbon, hydrogen, nitrogen, and oxygen content for woody biomass fuels were 40–55%, 5–7%, 2%, and 35–45%, respectively. Adeleke et al.[32] studied the elemental composition in Gmelina wood and Balogun et al.[33] in teak wood and observed an equivalent range of C, H, O and N. These results back up the conclusions of the current investigation.

In an in-depth analysis, the study found three clones: *Terminalia bellirica*- FCRITB 13, *Khayasenegalnesis*- KS 01, and *Mitragynaparvifolia*- MP 01 for high thermal conversion efficiency, and *Leuceanaleucocephala*- LL 15, *Melia dubia*- MD KP 01, and *Populusdeltoides*- PD SAT 1 for greater biomass productivity. The findings of the current suggested that, to draw a reliable conclusion, the examination ought to continue for atleast another two years, since the plantation is only a year old.

Conclusion

This study successfully evaluated the gasification potential of three fast-growing species. *Khaya senegalensis*- KS 01 demonstrated the most favorable results for syn-gas production, calorific value, and thermal conversion efficiency. The elemental composition analysis provided further insights into the fuel properties of these species. While these findings are promising, further research is recommended to confirm the long-term viability of these species for biomass gasification, potentially extending the study period for a more comprehensive evaluation.

References

[1] N. R. Bora *et al.*, "EVALUATION OF MULBERRY SPECIES (MORUS SPP.) AS A POTENTIAL SOURCE OF BIOENERGY THROUGH THERMOCHEMICAL CHARACTERIZATION AND GASIFICATION."

[2] H. Negi, D. C. Suyal, R. Soni, K. Giri, and R. Goel, "Indian scenario of biomass availability and its bioenergy-conversion potential," *Energies,* vol. 16, no. 15, p. 5805, 2023.

[3] C. Dupont, G. Boissonnet, J.-M. Seiler, P. Gauthier, and D. Schweich, "Study about the kinetic processes of biomass steam gasification," *Fuel,* vol. 86, no. 1-2, pp. 32-40, 2007.

[4] P. Ranganathan, "Preliminary techno-economic evaluation of 2G ethanol production with co-products from rice straw," *Biomass Conversion and Biorefinery,* vol. 12, no. 9, pp. 3673-3686, 2022.

[5] W. Doherty, "Modelling of biomass gasification integrated with a solid oxide fuel cell system," 2014.

[6] C. Higman and M. van der Burgt, "Gasification processes," *Gasification,* pp. 85-170, 2003.

[7] P. Basu, *Biomass gasification and pyrolysis: practical design and theory*. Academic press, 2010.

[8] Y. Zhang, Y. Zhao, X. Gao, B. Li, and J. Huang, "Energy and exergy analyses of syngas produced from rice husk gasification in an entrained flow reactor," *Journal of Cleaner Production,* vol. 95, pp. 273-280, 2015.

[9] L. Waldheim and T. Nilsson, "Heating value of gases from biomass gasification," *Report prepared for: IEA bioenergy agreement, Task,* vol. 20, 2001.

[10] W. Wang, "A Thermal Conversion Efficiency Study on Biomass Gasification of Arundo Donax and Woodchips," 2013.

[11] R. Goswami and R. Das, "Energy cogeneration study of red mulberry (Morus rubra)-based biomass," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* vol. 42, no. 8, pp. 979-1000, 2020.

[12] C. Hanping, L. Bin, Y. Haiping, Y. Guolai, and Z. Shihong, "Experimental investigation of biomass gasification in a fluidized bed reactor," *Energy & Fuels,* vol. 22, no. 5, pp. 3493-3498, 2008.

[13] M. Lapuerta, J. J. Hernández, A. Pazo, and J. López, "Gasification and co-gasification of biomass wastes: Effect of the biomass origin and the gasifier operating conditions," *Fuel processing technology,* vol. 89, no. 9, pp. 828-837, 2008.

[14] N. Nwokolo, P. Mukumba, and K. Obileke, "Gasification of eucalyptus wood chips in a downdraft gasifier for syngas production in South Africa," *International Journal of Renewable Energy Research (IJRER),* vol. 10, no. 2, pp. 663-668, 2020.

[15] S. M. Atnaw, S. A. Sulaiman, and S. Yusup, "Syngas production from downdraft gasification of oil palm fronds," *Energy,* vol. 61, pp. 491-501, 2013.

[16] T. Bridgwater, "Biomass for energy," *Journal of the Science of Food and Agriculture,* vol. 86, no. 12, pp. 1755-1768, 2006.

[17] C. Di Blasi, "Dynamic behaviour of stratified downdraft gasifiers," *Chemical engineering science,* vol. 55, no. 15, pp. 2931-2944, 2000.

[18] Y. Wang and C. M. Kinoshita, "Temperature fields in downdraft biomass gasification," in *Advances in thermochemical biomass conversion*: Springer, 1993, pp. 280-287.

[19] C. Gai and Y. Dong, "Experimental study on non-woody biomass gasification in a downdraft gasifier," *International Journal of hydrogen energy,* vol. 37, no. 6, pp. 4935-4944, 2012.

[20] P. N. Sheth and B. V. Babu, "Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier," *Bioresource technology,* vol. 100, no. 12, pp. 3127-3133, 2009.

[21] Z. A. Zainal, A. Rifau, G. A. Quadir, and K. N. Seetharamu, "Experimental investigation of a downdraft biomass gasifier," *Biomass and bioenergy,* vol. 23, no. 4, pp. 283-289, 2002.

[22] M. Dogru, C. R. Howarth, G. Akay, B. Keskinler, and A. A. Malik, "Gasification of hazelnut shells in a downdraft gasifier," *Energy,* vol. 27, no. 5, pp. 415-427, 2002.

[23] S. I. Islamova and E. K. Vachagina, "Study of energy conversion efficiency at thermal utilization of wood biomass," *Power engineering: research, equipment, technology,* no. 9-10, pp. 3-11, 2015.

[24] K. Umeki, K. Yamamoto, T. Namioka, and K. Yoshikawa, "High temperature steam-only gasification of woody biomass," *Applied energy,* vol. 87, no. 3, pp. 791-798, 2010.

[25] P. K. Sharma, A. K. Sharma, R. H. Pulla, and P. K. Sahoo, "Performance analysis of a medium-scale downdraft gasifier using Lantana camera biomass as feeding material,"

Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp. 1-15, 2020.

[26] C. Telmo, J. Lousada, and N. Moreira, "Proximate analysis, backwards stepwise regression between gross calorific value, ultimate and chemical analysis of wood," *Bioresource technology,* vol. 101, no. 11, pp. 3808-3815, 2010.

[27] A. M. Dadile, O. A. Sotannde, B. D. Zira, M. Garba, and I. Yakubu, "Evaluation of elemental and chemical compositions of some fuelwood species for energy value," *International Journal of Forestry Research,* vol. 2020, no. 1, p. 3457396, 2020.

[28] R. Kumar, K. K. Pandey, N. Chandrashekar, and S. Mohan, "Effect of tree-age on calorific value and other fuel properties of Eucalyptus hybrid," *Journal of Forestry Research,* vol. 21, pp. 514-516, 2010.

[29] A. Nordin, "Chemical elemental characteristics of biomass fuels," *Biomass and Bioenergy,* vol. 6, no. 5, pp. 339-347, 1994.

[30] M. Baqir, R. Kothari, and R. P. Singh, "Characterization and ranking of subtropical trees in a rural plantation forest of Uttar Pradesh, India, as fuel wood using fuel wood value index (FVI)," *Environment, Development and Sustainability,* vol. 21, no. 2, pp. 763-776, 2019.

[31] J. Dai, J. Saayman, J. R. Grace, and N. Ellis, "Gasification of woody biomass," *Annual review of chemical and biomolecular engineering,* vol. 6, no. 1, pp. 77-99, 2015.

[32] A. A. Adeleke, J. K. Odusote, O. A. Lasode, P. P. Ikubanni, M. Madhurai, and D. Paswan, "Evaluation of thermal decomposition characteristics and kinetic parameters of melina wood," *Biofuels,* vol. 13, no. 1, pp. 117-123, 2021.

[33] A. O. Balogun, O. A. Lasode, and A. G. McDonald, "Devolatilisation kinetics and pyrolytic analyses of Tectona grandis (teak)," *Bioresource technology,* vol. 156, pp. 57-62, 2014.