Air Gasification of Banana (*Musa spp.*) Residues to Produce Biofuels

Adewale George Adeniyi (✉ adeniyi.ag@unilorin.edu.ng)

University of Ilorin <https://orcid.org/0000-0001-6615-5361>

Joshua O. Ighalo

University of Ilorin Faculty of Engineering and Technology

Research

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Abstract

Thermochemical conversion of biomass is a technique used in recovering its energetic content and for the production useful biofuels. A lot of wastes/residues are generated from the harvesting and consumption of banana fruits. This study developed an ASPEN Plus model for the gasification of banana (*Musa Spp.*) residues pseudo-stem, the peels and the leaves. The model will be used to study the effect of gasification temperature, gasification pressure and air-fuel ratio (AFR) on the selectivity of the chemical species in the product stream. For all three residues, the selectivity of hydrogen increases with temperature with temperature. At the optimum temperature, the hydrogen molar selectivity in the product stream is 56% (900°C), 55% (900°C) and 53% (700°C) for pseudo-stem, peels and leaves respectively. At the optimum atmospheric pressure, the hydrogen molar percentage in the product stream was 48%, 49% and 50% for pseudo-stem, peels and leaves respectively. At the optimum AFR, the hydrogen selectivity in the product stream is 55%, 52% and 46% for pseudo-stem, peels and leaves respectively. All three residues are reasonably good feedstock for the gasification process but the pseudo-stem possesses a marginal advantage over the others.

1. Introduction

Minimisation of fossil fuel utilisation by other renewable fuels is of paramount interest to energy and environmental engineers. In this regard, biomass is an important renewable energy source [1].

Thermochemical conversion of biomass is a technique used in recovering its energetic content and for the production useful products (biofuels). Some of the techniques include pyrolysis [2, 3], gasification [4, 5], combustion [6] and steam reforming [7].

Banana (*Musa Spp.*) plant that is often mistakenly referred to as a "tree" is a large single-fruit bearing herbal plant widely grown in West Africa [8, 9]. Having a cylindrical stem, it is tall and robust and can grow to a height of 0.8 m to around 7.5 m [10, 11]. A lot of wastes/residues are generated from the harvesting and consumption of banana fruits and these includes rotten fruit, rhizome, leaves, pseudo-stem, peels and empty fruit bunch [12]. These banana wastes possess a huge energy potential as have been revealed by studies [13, 14]. These energy content can be exploited by gasification. Gasification is a process that converts carbonaceous materials into synthesis gas, by heating the material to a very high temperature (usually greater than 700°C) without combustion and with a controlled amount of oxygen [15].

ASPEN Plus has been used to simulate the biomass gasification process to study certain such as preheating effect [16], gasifying agent effect [17], nature and composition of product [18], preliminary investigation [19], comparative performance analysis [20] and general process modelling [21]. Though gasification of other biomass has been studied, there are no reports on the gasification of banana (*Musa Spp.*) residues (at least within the scope of the authors' search). The aim of this study is to develop an ASPEN Plus model for the gasification of banana (*Musa Spp.*) residues. The residues to be considered in the current investigation are the pseudo-stem, the peels and the leaves. The model was used to study the

effect of gasification temperature, gasification pressure and air-fuel ratio (AFR) on the selectivity of the chemical species in the product stream. Comparisons between the different residues will be made so we can gain a proper understanding of the potential of each residue as a gasification feedstock based on the nature of their composition.

2. Methodology

The simulation was performed using ASPEN Plus v8.8. ASPEN Plus can perform most core chemical engineering calculations such as vapour liquid equilibrium, mass and energy balance, heat transfer, mass transfer and chemical kinetics. The software is especially suited for gasification studies [4]. In this section, a detailed explanation of the method used in developing the ASPEN Plus model was presented. For a thermodynamic simulation such as this, the software uses a minimisation of Gibbs free energy calculation technique. Much detail about the technique is also available in open literature [7, 22].

2.1 Components Specifications

A number of conventional components were considered in the simulation. These include solid carbon (C), hydrogen gas (H_2), nitrogen gas (N_2), oxygen gas (O_2), sulphur (S), carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), water (H_2O) and silicon oxide (SiO_2). Silicon oxide was added to the simulation to represent ash. The ultimate and proximate analysis of biomass is required to model it in ASPEN simulation environment because it is considered as an unconventional material and hence do not appear on the component listing. The information of the ultimate and chemical analysis of banana (*Musa Spp.*) residues in Table 1 were presented by Kabenge, Omulo, Banadda, Seay, Zziwa and Kiggundu [23]. The proximate analysis presented was however re-calculated in our previous paper (with adequate justifications) to be suitable for ASPEN simulations [2].

Table 1
Proximate and Ultimate Analysis of different banana
(*Musa Spp.*) residues [2, 23].

	Pseudo-stem	Peel	Leaves
Proximate analysis (wt% dry basis)			
Moisture	7.98	11.56	6.67
Fixed Carbon	1.12	2.39	7.09
Volatile Matter	82.29	77.84	77.79
Ash	8.61	8.21	8.45
Ultimate/Elemental analysis (wt% dry basis)			
Carbon	33.46	35.65	38.57
Hydrogen	6.44	6.19	6.44
Sulphur	0.04	NL	NL
Oxygen	49.94	45.94	43.49
Nitrogen	0.8	1.94	0.8
Ash	9.36	9.28	9.05
Chemical analysis (wt%)			
Cellulose	38.48	9.9	35.58
Hemicelluloses	25.36	41.38	23.46
Lignin	5.77	8.9	10.58
Extractives	NS	NS	NS
Heating/Calorific values (MJ/Kg)			
High Heating Value	15.04	16.15	17.57
Low Heating Value	13.63	14.80	16.16
NS = Not stated, NL = Negligible			

2.2 Model Specifications

The global setting of the simulation was set to MIXCINC to reflect that there are conventional and non-conventional solids alongside the conventional components. The choice also reflects that the particle sizes of the biomass will not be considered. The specific property methods for enthalpy and density were chosen as HCOALGEN and DGOALIGT respectively [2]. The global calculation method of the simulation was the Peng-Robinson with Boston-Mathias alpha function equation of state (PR-BM). Alpha is a

temperature dependent parameter that is added to the original Peng-Robinson equation to improve the prediction of pure component vapour pressure at very high temperatures. It has been used previously in pyrolysis simulations on ASPEN plus [2, 22].

In converting the non-conventional biomass to simulation components, the method utilised and validated by Atikah and Harun [4] was replicated. The RYIELD block was given initial assumptions of mass yield same as those of Atikah and Harun [4]. A CALCULATOR block was however added to the simulation to specify the actual yield of the conventional simulation components based on the information of the proximate and ultimate analysis. The Fortran formulas used are also given by Atikah and Harun [4].

$$\text{FACT} = (100 - \text{WATER}) / 100$$

$$\text{SULF} = \text{ULT6} / (100 * \text{FACT})$$

$$\text{N2} = \text{ULT4} / (100 * \text{FACT})$$

$$\text{CARB} = \text{ULT2} / (100 * \text{FACT})$$

$$\text{O2} = \text{ULT5} / (100 * \text{FACT})$$

$$\text{H2O} = \text{WATER} / 100$$

$$\text{ASH} = \text{ULT1} / (100 * \text{FACT})$$

$$\text{H2} = \text{ULT3} / (100 * \text{FACT})$$

All the parameters on the left side of the Fortran equations (with the exception of FACT) are 'block-var' style export variables, defined for 'Split' block and classified as 'MASS-YIELD.' All the parameters on the right side of the Fortran equations (with the exception of FACT and WATER) are 'compattr-var' style import variables defined for 'BIOMASS' stream and attributed to ULTANAL. 'WATER' is the same for other import variables but is related to Proximate Analytical Water (PROXANAL). FACT is a general line of code in the equations that the algorithm can solve and then use as input in other lines of code.

2.3 Model Description

Different blocks were integrated together to represent/model the different aspects of the gasification process. The process flow diagram of the simulation is presented in Fig. 1. A difference in the current simulation with that of Atikah and Harun [4] is the absence of pre-drying stage. This was incorporated in the current simulation because the information of banana residues proximate and ultimate analysis in Table 1 [2] was for an already dried biomass sample (in an air-dried basis). This approach is considered rather appropriate for a study such as this where comparisons of different residues will be made. Ordinarily, the moisture content will not only vary from one residue to the other, but will vary from even from one sample to the other (of same residue). Parallels can only be comfortably drawn when all samples are considered on a dry basis.

The gasification process was computed by 'RGIBBS' block referred to as GASIFIER in the simulation. The calculations of phase and chemical equilibrium is based on the minimisation of Gibbs free energy calculation method. The 'BREAK' block is for modelling the first stage pyrolysis of the biomass at the inception of heating and the SEP block is for separating the char and ash from the gaseous products. The simulation ambient temperature and pressure were specified as 25°C and 1 atm respectively. The different banana residues (100 kg/hr basis) was fed into the system at ambient conditions without the consideration of particle sizes. A summary of the blocks in the simulation and their descriptions are presented in Table 2. The model will be used to study the effect of gasification temperature and pressure and air fuel ratio on the quantity and quality of the synthesis gas produced. The temperature and pressure of gasification will be varied from the RGIBBS block. The temperature range for the study is 400-1000°C and the pressure range is 1 to 5 atm. The air fuel ratio (mass ratio of the air to the biomass stream) will be varied from the flowrate of the input air stream. It is essentially a measure of the equivalence ratio of the combustion. The and air-fuel ratio (AFR) will be varied from 0.01 to 1 kg/kg.

Table 2
Description of model blocks and streams

ASPEN Plus ID	Name	Description
MATERIAL	BIOMASS	The stream representing the banana residues feedstock specified at 100 kg/hr
RYIELD	BREAK	For modelling the first-stage pyrolysis of the biomass.
CALCULATOR	DECOMP	For imposing the characterisation information on the way the RYIELD block converts the non-conventional stream to conventional components
MATERIAL	OUT1	The output stream of conventional components from the RYIELD block.
MATERIAL	AIR	The air supply for the gasification of the biomass
RGIBBS	GASIFIER	Calculation of the composition of the products through the minimisation of Gibbs free energy
MATERIAL	OUT	For modelling the air gasification of the biomass
SSPLIT	SEP	Separation of the char from the product vapour by specifying split ratio
MATERIAL	SYN-GAS	The product stream of synthesis gas and Nitrogen
MATERIAL	BIO-CHAR	The product stream of biochar

In developing the model, several assumptions were considered. The pyrolysis simulation model prepared with Aspen PLUS V8.8 is a steady-state model hence there is no time function. The operation of the gasifier is isothermal and pressure drop is neglected in the system. Heat loss from the gasifier is neglected. All sulphur in the biomass is considered to be organic sulphur. The organic chlorine in the

biomass is assumed to be insignificant and is not considered in the study. No oxides of nitrogen and sulphur are formed. All elements take part in the chemical reaction except and there are no specified inert. All gasification reactions are considered to take place at equilibrium. The ash is assumed to be silicon oxide alone. The biochar is assumed to be of elemental carbon and ash alone. No particle size distribution was considered in the simulation.

3. Results And Discussion

The simulation was run successfully without any errors after the methodology was implemented. Though the product stream is composed of nitrogen gas (from the air), the syn gas itself will be considered as nitrogen free hence the species to be examined in the product stream are CO, CO₂, CH₄ and H₂. The performance index is the percentage molar composition of each of these species in the product stream. Nitrogen is an inert species in the reacting system and its composition is usually unchanging hence not included. The model itself (with the exception of the pre-drying stage) is a near replication of that of [Atikah and Harun \[4\]](#) which has already been validated for biomass gasification. On this premise, we proceed to examine how the process factors affect the selectivity in the product stream.

3.1 Effect on temperature on product selectivity

Figures 2a-c reveals the effect of temperature on the selectivity of different chemical species at 1 atm and 0.1 AFR for pseudo-stem, peels and leaves. It can be observed that for all three residues, the selectivity of hydrogen and carbon monoxide increases with temperature while carbon dioxide and methane drops with temperature. This has also been observed for the gasification of poultry litter [24] and switchgrass [25]. The optimum temperature for hydrogen selectivity for pseudo-stem and peels is 900°C while that of leaves is 700°C. At these optimum conditions, the hydrogen molar selectivity in the product stream is 56%, 55% and 53% for pseudo-stem, peels and leaves respectively. The rise in hydrogen selectivity from lower temperatures is steeper for leaves than for the other residues. These findings of are quite interesting because though we can ascertain that all three residues will give good product yield, the leaves will require a lesser gasification temperature (albeit at a slightly lesser selectivity).

Figures 2 (a-c). Effect of temperature on gas composition at 1 atm and AFR 0.1 kg/kg for (a) Pseudo-stem (b) Peels (c) leaves

3.2 Effect of pressure on product selectivity

Figures 3a-c reveals the effect of pressure on the selectivity of different chemical species at 600°C and 0.1 AFR for pseudo-stem, peels and leaves. It can be observed that for all three residues, the selectivity of the lighter chemical species (H_2 and CO) drops with increasing pressure and those of the heavier species rise. It is well understood that for thermochemical processes (and chemical systems in general) at equilibrium, an increase in pressure will shift the equilibrium in favour of the heavier species and vice versa [7]. We can then surmise that the optimum pressure for the gasification of banana residues is at atmospheric pressure. At this pressure (and at 600°C and 0.1 AFR), the hydrogen molar percentage in the product stream was 48%, 49% and 50% for pseudo-stem, peels and leaves respectively.

Figures 3 (a-c). Effect of Pressure on gas composition at 600°C and AFR 0.1 kg/kg for (a) Pseudo-stem (b) Peels (c) leaves

3.3 Effect of air-fuel ratio (AFR) on product selectivity

Figures 4a-c reveals the effect of AFR on the selectivity of different chemical species at 600°C and 1 atm for pseudo-stem, peels and leaves. After an initial lag of up to 0.4 kg/kg AFR, the hydrogen content was improved except for the leaves that experienced a continual gradual decline. What was quite conspicuous for all three residues in the drop in methane and rise in CO_2 content with increasing AFR. This has also been observed for the gasification of poultry litter [24] and switchgrass [25]. The greater availability of oxygen (from air) at higher temperatures ensure a more intense gasification of the carbon load leading to higher oxygenated products and lesser methane. At the highest AFR studied (1 kg/kg), the hydrogen selectivity in the product stream is 55%, 52% and 46% for pseudo-stem, peels and leaves respectively.

Figures 4 (a-c). Effect of AFR on gas composition at 600°C and 1 atm for (a) Pseudo-stem (b) Peels (c) leaves

Conclusion

From the study, several key deductions were made. It was observed that for all three residues, the selectivity of hydrogen increases with temperature. At the optimum temperature, the hydrogen molar selectivity in the product stream is 56% (900°C), 55% (900°C) and 53% (700°C) for pseudo-stem, peels and leaves respectively. It was also observed that the selectivity of hydrogen drops with increasing pressure for all residues. At the optimum atmospheric pressure (and at 600°C and 0.1 AFR), the hydrogen molar percentage in the product stream was 48%, 49% and 50% for pseudo-stem, peels and leaves respectively. After an initial lag of up to 0.4 kg/kg AFR, the hydrogen content was improved except for the leaves that experienced a continual gradual decline. At the highest AFR studied (1 kg/kg), the hydrogen selectivity in the product stream is 55%, 52% and 46% for pseudo-stem, peels and leaves respectively (and at 600°C and 0.1 AFR). Overall, though all three residues are reasonably good feedstock for the gasification process, the pseudo-stem possesses a marginal advantage over the others. This study is one of the very first to consider the potentials in banana residues as feedstock for the gasification process. The findings have opened up the potentials of this biomass for exploitation via this thermochemical technique.

Declarations

1. Availability of data and materials

Not Applicable

2. Competing interests

NIL, the authors declare that there are no conflicts of interest and the article does not contain any studies involving human or animal subjects.

3. Funding: NIL, no funding was received

4. Authors' contributions

Adeniyi, Adewale George did the setting out of the background to the study, wrote the introduction and edited the complete manuscript.

Ighalo Joshua O did the process flow diagram design, process simulation, methodology set up and discussion of results

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6. Authors' information (optional)

Adewale Adeniyi is a Lecturer at the Department of Chemical Engineering, University of Ilorin, Nigeria. He holds a Ph.D in Chemical Engineering from Ladoke Akintola University of Technology, Ogbomoso, Nigeria. He has interests in process and product development with focus on computer-aided modelling and optimisation of chemical process systems, biofuels production and solid waste recycling. He has

been involved in utilizing waste materials & technologies for pollution abatement, sustainable product and process developments for diverse industrial and military uses.

Joshua O. Ighalo holds his Masters Degree in Chemical Engineering (2020) from Chemical Engineering Department at the University of Ilorin. He holds bachelor degree in chemical engineering (2015) from the University of Benin. His research interest includes computer-aided modelling and optimisation of chemical process systems, biofuels, solid waste management and environmental pollution control.

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Figures

Figure 1

Process flow diagram of the simulation

(a)

(b)

(c)

Figure 2

a-c). Effect of temperature on gas composition at 1 atm and AFR 0.1 kg/kg for (a) Pseudo-stem (b) Peels (c) leaves

Figure 3

a-c). Effect of Pressure on gas composition at 600oC and AFR 0.1 kg/kg for (a) Pseudo-stem (b) Peels (c) leaves

Figure 4

(a-c). Effect of AFR on gas composition at 600oC and 1 atm for (a) Pseudo-stem (b) Peels (c) leaves