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HYDROTHERMAL GASIFICATION AND PYROLYSIS TREATMENT OF FRUIT WASTE FOR SYNGAS PRODUCTION: PROCESS SIMULATION AND OPTIMIZATION

A. A. Yusuf[a], M. Ibrahim[a]*, K. Garba[a], A. A. Jock[b], I. M Muhammad[a] and I. Jato[a,c]
[a]Department of Chemical Engineering, Abubakar Tafawa Balewa University, PMB 0248, Bauchi, Bauchi State, Nigeria, [b]Department of Chemical and Petroleum Engineering, University of Uyo, Uyo State, Nigeria, Department of Chemical Engineering, Federal Polytechnic, N'Yak, Sendam LGA, Plateau State, Nigeria

**To whom correspondence should be addressed, Maryam Ibrahim (Ph.D), Tel: +23481 33277270*
Email:mibrahim@atbu.edu.ng

ABSTRACT
In the present study, the efficient utilization of fruit waste biomass in gasification and pyrolysis at steady-state equilibrium conditions was modelled using ASPEN Plus software. The effect of gasification temperature and pressure and decomposition temperature and pressure were investigated to obtain the optimum operating parameters that gives the highest yield of the syngas for the gasification process of banana peel, orange peel, mango endocarp and water melon peel. The result of the gasification show mango endocarp have the highest amount of syngas (197.302 kg/h) followed by the other fruits in the order water melon peel, orange peel and banana peel as 195.38, 193.386, and 148.09 kg/h respectively. Pyrolysis of banana peel gave the highest amount of syngas 93.478 kg/h compare to pyrolysis of mango endocarp, water melon peel and orange peel with syngas yield of 91.18, 89.07, and 87.013 kg/h respectively. The gasification temperature is most significant parameter and the optimum operating parameters for syngas yield at 197.534 kg/h in the gasification of mango endocarp are decomposer temperature, decomposer pressure, gasifier temperature, gasifier pressure and desirability of 610 °C, 1.081 atm, 841 °C, 1.012 atm and 1 respectively. This demonstrate the potential of mango endocarp as a vigorous gasification candidate for syngas production.

Keywords: Gasification, Pyrolysis, Fruit Waste, Syngas, Optimization

INTRODUCTION
Rapid population growth around the world causes a high demand for energy and stringent environmental regulations on the use of fossil fuels, which has turned into a major global problem. Biofuels and other renewable energies have lately been discovered as a suitable substitute for conventional fuels in order to address these issues. (Zhou *et al.,* 2024).
The World Bank's "Safe Food Imperative" for 2023 states that the cost of treating diarrhea caused by contaminated fruit was roughly $10 per case, meaning Nigeria would lose roughly $6 billion USD a year in treatment costs (Duo *et al.,* 2021; Wu *et al.,* 2022). Nevertheless, fruit waste makes up around 20.6% of all municipal solid waste produced in Nigeria. If not properly managed, fruit waste can lead to serious environmental issues like eutrophication, global warming, water and soil pollution, and other health-related problems because it is highly biodegradable and fermentable (Din *et al.,* 2023). Landfill trash can be turned from a waste product into a resource by being burned as fuel. Due to the high degree of variability in municipal solid waste, identifying possible energy sources by dissecting the rubbish into its constituent parts is necessary for the creation of an effective waste-to-energy infrastructure. The majority of food created from organic resources, such as vegetables, bananas, yams, and oranges of which are generated by the world's expanding agricultural economy but are frequently thrown away (Arte *et al.,* 2024). Organic resources are renewable and can be converted to energy.
Syngas is a fundamental raw material used in the production of fuels and chemicals, both of which are predicted to have rapid market expansion. In the chemical industry, syngas is already a crucial intermediary and is predicted to have a growing market as a precursor to bulk chemicals like

methanol and synthetic fuels produced by the Fischer-Tropsch process. The chemical industry of the future is expected to rely heavily on methanol as a platform chemical for the production of aromatics and olefins for polymers. By 2050, the demand for polymers is predicted to triple, which would result in a huge increase in the demand for methanol (Zhang *et al.,* 2024). However, as a means of facilitating the reduction of greenhouse gas emissions in the shipping and aviation industries, synthetic fuels may see even more expansion in the upcoming decades. Consequently, a significant compound annual growth rate of more than 6% is predicted for the global syngas demand (Ram & Salkuti, 2023). The two main processes used to make syngas nowadays are coal gasification and natural gas steam reforming. The manufacture of syngas from fossil fuels releases a lot of greenhouse gases. Moreover, extra greenhouse gas emissions result from the products' disposal at the end of their life cycle, which releases the carbon derived from fossil fuels that was previously contained in them. Accordingly, syngas based on alternative feedstock is necessary to achieve significant reductions in GHG emissions (Güleç *et al.,* 2024).

In recent years, many interesting alternative syngas production pathways have been investigated. Gasification, pyrolysis, and anaerobic digestion are methods for producing bio-based syngas. Lately, pyrolysis and gasification have gained a lot of attention as techniques for recovering energy from bio-waste. It can replace natural gas in the standard syngas production process using steam reformation. Alternatively, biomass can be directly converted into syngas through gasification, which involves high temperatures and the presence of a gasifying agent such as oxygen or steam. Similarly, biomass can be converted into syngas by pyrolysis, which consume low energy (Wang *et al.,* 2024).

Several studies have been conducted to develop a novel thermochemical conversion pathway using waste materials from daily activities, such as algae, industrial waste, and animal waste, to preserve perishable goods like fruit, which can be costly to preserve (Lee *et al.,* 2023). Consequentlty, farmers are left with rot fruits that may later be dispose to the landfill as source of manure (Maag *et al.,* 2022). Even though producing syngas using thermochemical processes like pyrolysis and gasification is thought to be one of the most promising ways to produce energy, there are still significant obstacles in the way of its advancement.

The utilization and disposal of abundant fruit waste due to its perishability generates large number of organic wastes as unavoidable by-products. Fruit waste which is contributing highly to the environmental hazard around major markets and industries across the world can be transformed into biofuels through thermochemical processes such gasification, pyrolysis and hydrothermal liquefaction (Wani *et al.,* 2024). Thermochemical processes present the necessity of dry feedstock to achieve a positive energy balance and of further processes to upgrade the raw product in order to obtain commercially valuable fuel. Additionally, the developed thermochemical conversion pathways are still striking because of the low yield of the products that pave a way to raise the investment cost of the processes. Thus, this research work tends to optimize the thermochemical conversions into sustainable form via checking the potentiality of different feedstock for syngas production using pyrolysis and gasification thermochemical conversion process using Aspen plus simulation approach.

Process Simulation Approaches

Data collection

In order to replicate fruit waste, process data on the various fruit waste was obtained from literature. These include mass flowrate, temperature, and pressure as equipment operating conditions.

Aspen PLUS® modelling and simulation procedure

Aspen PLUS® was used to model the pyrolysis and gasification process for the production of syngas by the use of waste fruit as the feed stock. This will be based on condition and parameters obtained from the literature. Detail of the modelling and simulation procedure to be carried out is presented in Table 1 as in the Aspen PLUS environment:

Table 1: Stepwise Procedure for Modelling and Simulation in Aspen Plus Environment

Step	Task
1	Start Aspen Plus Software Package
2	Choose chemical compounds involved
3	Select suitable thermodynamic model
4	Arrange the flowsheet
5	Choose units and specify feed stream properties
6	Fill in Equipment specifications
7	Choose output parameters to be displayed
8	Run the model/simulation
9	Collect results

Aspen PLUS® modelling and simulation procedure

The assumptions were drawn during the model development and simulation of the fruits waste hydrothermal gasification/pyrolysis treatment for syngas production as follows;

1. Simulation was run at steady state
2. Biomass and Ash were modelled as non-conventional
3. Model is kinetic free
4. Simulation is conducted at constant temperature
5. Char was modelled as solid carbon
6. Tar free process formation.

Process description

2.4.1 Pyrolysis

Fruit waste pyrolysis is done using the Aspen Plus Simulator; Figure 1 shows the established process flow diagram for fruit waste pyrolysis for the production of sustainable syngas. The residual fruit peels from oranges, bananas, water melons, and mango endocarps were each used as feedstock for the pyrolysis process. The decomposed product was injected into the pyrolysis reactor where the each fruit waste fruit pyrolyzed. The waste fruit was fed into the dryer to remove the water content in the biomass, which was collected and passed to the steam generation section. The dry product was then passed to the decomposer to enable conversion of non-conventional component to conventional. The pyrolysis product was then sent to a cyclone, where the bottom product char was deposited as solid and the top product gases were removed as syngas.

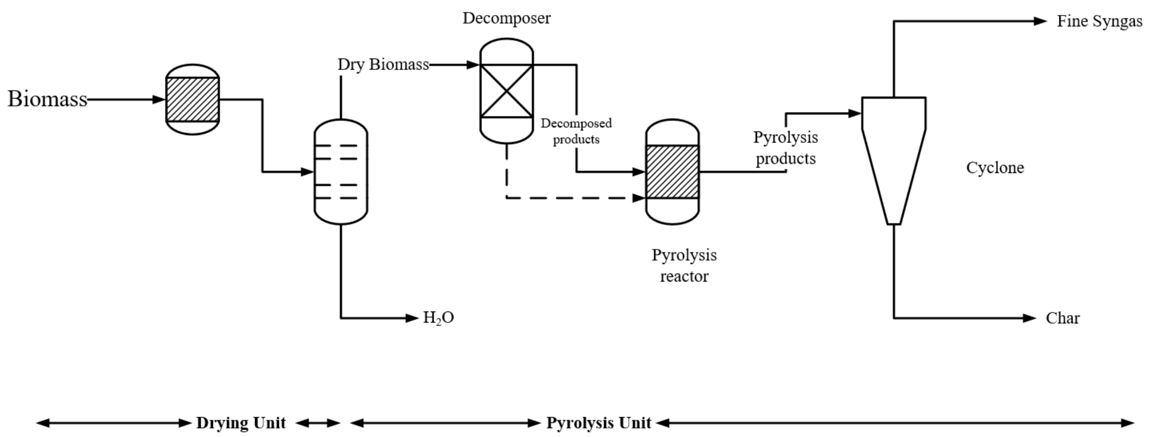

Figure 1: Process Flow Diagram of Pyrolysis Treatment of Fruit Waste for Syngas Production

2.4.2 Gasification

The process flow diagram for gasification treatment of fruit waste for syngas production was created and is shown in Figure 2. For this investigation, fruit wastes such banana, watermelon, orange, and mango endocarp peels were used. Each of the sample is treated separately. The waste fruit was fed into the decomposition reactor, and the conventional stream was injected into the gasification reactor, where gasification occurred to yield syngas, char, and ashes. The cyclone that removed the fine syngas from the gasification product was used to separate it from the bottom product, which is the char and ashes.

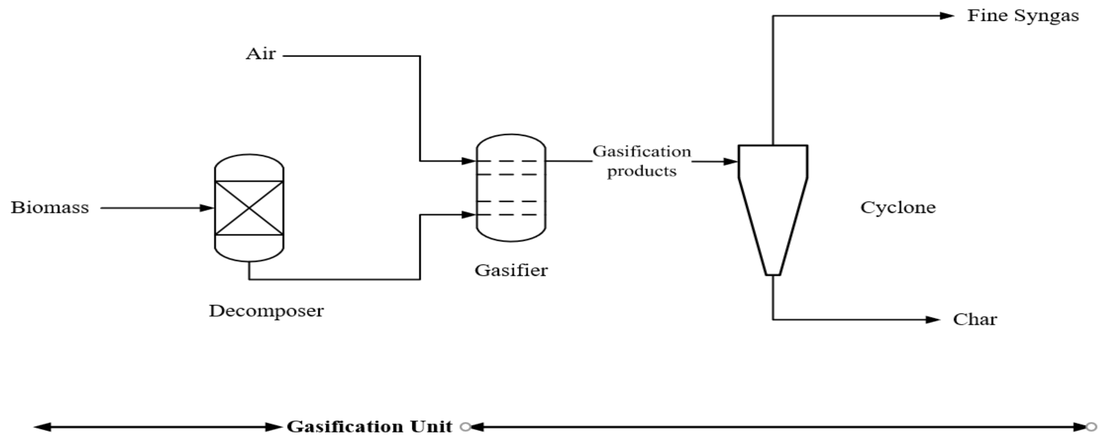

Figure 2: Process Flow Diagram of Gasification of Fruit Waste for Syngas Production

Optimization Using Response Surface Methodolog

The Central Composite Design (CCD) of response surface methodology (RSM) was utilized to model and optimize the values of process parameters, such as the temperature and pressure of the gasification reactors, on the syngas yield through gasification process. It has been shown to be a widely accepted, user-friendly, and effective statistical expression design tool. When compared to other methods, the primary benefit of using RSM as an experimental design methodology is its speed and low execution time for the optimization issue. As a result, fewer experimental experiments may be needed to determine how many components interact and what impact they have on a system (Kariim *et al.,* 2023). This methodology is typically used in situations where the process involves few experimental settings. By using RSM, a second-order polynomial equation can be fitted to give a mathematical relationship between a number of parameters and the experimental results. Therefore, it is recommended to use Equation 1 to create a quantitative relationship between the syngas yield and four independent variables. However, there are four separate factors that affect gasification processes. This formula is a great tool for assessing the impact and determining the ideal values of four chosen experimental parameters on the syngas yield (kg/h).

Syngas yield (Kg/h) = $\beta_o + \beta_1A + \beta_2B + \beta_3C + \beta_4D + \beta_5E + \beta_6AB + \beta_7AC + \beta_8AD + \beta_9AE + \beta_{10}BC + \beta_{11}BD + \beta_{12}BE + \beta_{13}CD + \beta_{14}CE + \beta_{15}DE + \beta_{16}A^2 + \beta_{17}B^2 + \beta_{18}C^2 + \beta_{19}D^2 + \beta_{20}E^2$... (1)

Where β_0 is a constant; β_1 to β_5 are the first-order main effect constants, and β_6 to β_{20} are the second-order main effect constants, of the regression equation.

Additionally, in order to assess the suitability of the proposed model in light of the syngas yield experimental data, the coefficient of determination (R^2) and adjusted coefficient of determination (R^2 adjusted) will be calculated. In addition, the plot of actual values against anticipated values and the normal distribution of the residuals were used. The statistical analysis of the responses was conducted using analysis of variance (ANOVA), with a probability critical level (p-value) of 0.05 being taken into consideration to indicate the statistical importance of the parameters in the suggested model. Tables 2 displays the range and amounts of the factors according to the experimental design:

Table 2: Variables, level of design experiments, and RSM Design for Gasification

Variable	Code	Range and level Low level (− 1)	Range and level High level (+ 1)
Decomposer Temperature	A	200	800
Decomposer Pressure	B	0.8	1.5
Gasifier Temperature	C	300	1000
Gasifier pressure	D	0.5	1.5

RESULTS AND DISCUSSION

Aspen plus model development

The waste fruit pyrolysis and gasification was carried using Aspen plus simulator; Figure 3 and Figure 4 showed the developed Aspen plus process flow diagram for the pyrolysis and gasification of fruit waste for sustainable syngas production respectively. While, Table 3 and Table 4 presents the Aspen block models used for the pyrolysis and the gasification of fruit waste in the Aspen plus environment respectively.

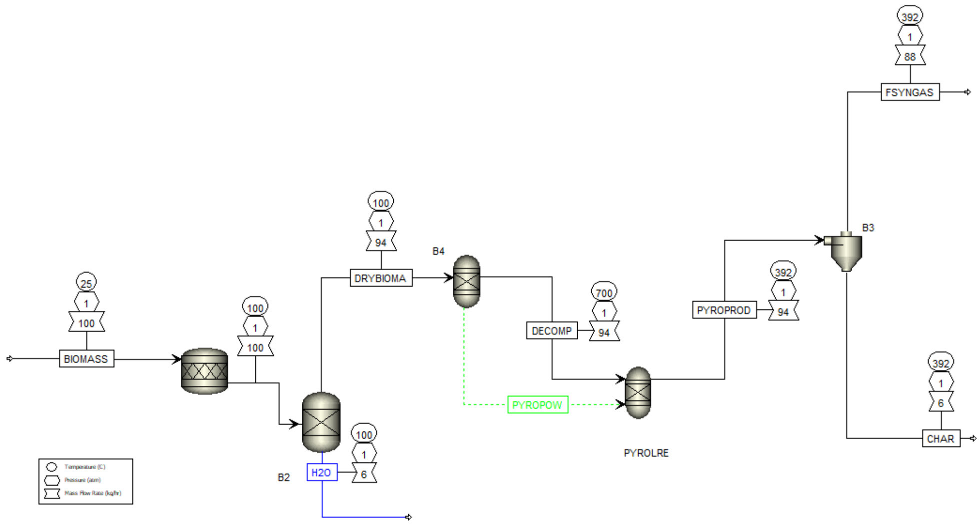

Figure 3: Process Flow Diagram of Pyrolysis of Fruit Waste for syngas Production

Table 3: Description of Unit Operations Used for Pyrolysis in Aspen Plus

Block Specification	Aspen Plus bock name	Description
Dryer	RStioc	Remove moisture from the biomass
SEP1	Sep	Separation of dry biomass from moisture content
Decomp	RYield	Used to decomposed non-conventional component to conventional
Pyrolysis	RGibb	Pyrolysis reaction take place with availability of kinetic data
Cyclone	Cyclone	Separation of the pyrolysis product the top gas and the bottom char

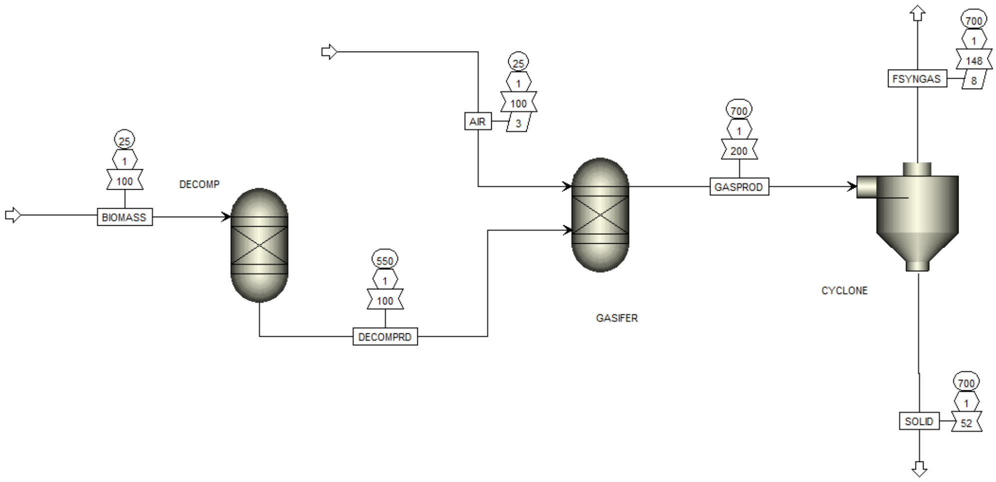

Figure 4: Process Flow Gasification Treatment of Fruit Waste for Syngas Production

Table 4: Description of Unit Operations Used for Gasification in Aspen Plus

Block Specification	Aspen Plus bock name	Description
Decomp	RYield	It used to convert non-convention to conventional component
Gasifier	R-Gibbs	Used for gasification reaction due to its ability to separate conventional component into solid, liquid and gas
Cyclone	Cyclone	Separate the fine syngas from other solids

The developed Aspen PLUS® Models validation

Validation was done using available experimental data from literature to confirm the stability of the developed models, ensuring the models' quality and stability. The Aspen Plus model for pyrolysis of waste fruit validation considered syngas composition using the same input parameters used by Alnouss et al (2021) in their research work. The parameters were fed and simulated in the developed models. The results demonstrate a perfect agreement of the presented model with the reported literature. The compositions of syngas produced from the pyrolysis process is showing only a <1% error difference. However, the gasification Aspen Plus model was validated using existing data from the work of Li et al., (2021), gasification reactor temperature 600^{O}C, steam was used as gasification agent and steam to biomass ratio of 1.0. It was observed that the gasification product composition of the experimental results is very much close to results obtained from this current work.

Amount of Syngas Produced using pyrolysis and gasification process for different fruit waste

Figure 5 presents the results of amount of Syngas produced from the developed pyrolysis and gasification process for different fruit waste. It can be observed from the Figure that gasification process gave the highest amount of syngas produced. This may be attributed the presence of gasification medium such as steam and air which aided the yield of syngas in the gasifier (Valizadeh *et al.,* 2022, Anniwaer *et al.,* 2023). The result of the gasification show mango endocarp have the highest amount of syngas (197.302 kg/h) followed by the other fruits in the order water melon

peel, orange peel and banana peel as 195.38, 193.386, and 148.09 kg/h respectively. The highest amount of syngas from the gasification of mango endocarp was due to the high value for the volatile matter content in the mango endocarp compare to the melon peel, orange peel and banana peel with less volatile matter. The obtained result from this research work is similar to the result obtained by Ali & Gunjo, (2024) in their work.
The results of the pyrolysis is presented in Figure 5, it can be observed that lower amount of syngas yield was obtained when compared to gasification. This may be as a result of the drying process in the pyrolysis process which led to low volatile matter contents of the fruit waste. In addition, the pyrolysis was carried out at lower temperature compare to gasification that will enable destruction of the inner structural bond of the fruit waste. Pyrolysis of banana peel gave the highest amount of syngas 93.478 kg/h compare to pyrolysis of mango endocarp, water melon peel and orange peel with syngas yield of 91.18, 89.07, and 87.013 kg/h respectively.
Comparison of the results of gasification and pyrolysis of fruit waste, generally the results obtained gasification process shows high rate of syngas production. The significant difference in percentages for mango endocarp, water melon peel, orange peel and banana peel are 53.81, 54.41, 54.99, and 36.87 % respectively.

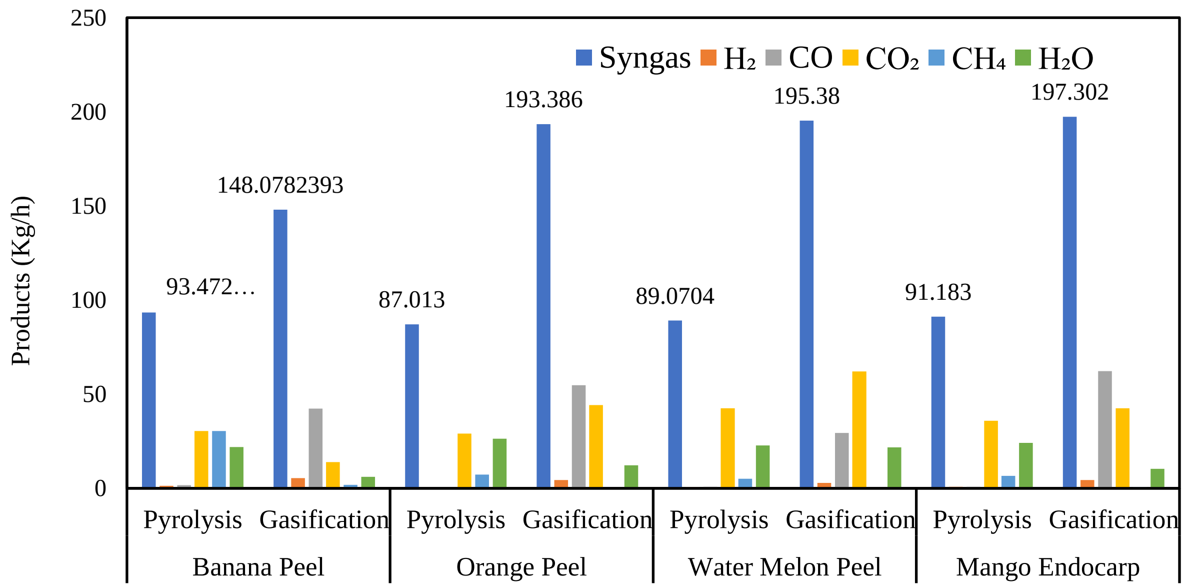

Figure 5: Amount of Syngas Produced using pyrolysis and gasification process for different fruit waste

Comparison of the current results with literature

Table 5 shows that, when compared to the works of other researchers, mango endocarp produced the greatest amount of syngas by steam gasification methods. This further demonstrated the mango endocarp has a potential as a vigorous gasification candidate for syngas production.

Table 5: Comparison of Current Results with Literature on Gasification Processe

SNo	Author	Types of food waste	Conversion process	Syngas (kg/h)
1.	(Koshariya *et al.*, 2024)	Solid food waste	water gasification reactor	139.15
2.	Waheed *et al.*, 2024	orange, yam, and potato peels	Steam gasification using Aspen plus	105 .02

3.	(Yin *et al.*, 2024)	municipal sludge + food waste	Co-gasification	165.27
4.	(Alouani *et al.*, 2024)	Food waste	Aspen gasification models for both the fixed and fluidized-bed gasifiers integrated	185.23
6.	Current work	Mango endocarp	Aspen plus steam gasification	197.302

Numerical Optimization

Gasification of Fruit Waste (mango endocarp) Design of Experiment

Table 6 displays the design of experiment created using Design Expert software. The Response Surface Methodology using central composite design was used to develop the experiment for gasification of mango endocarp.

Table 6: Results of ANOVA for Gasification of Mango endocarp

	Factors				Response
Runs	Dcomtemp (℃)	Decompress (atm)	Gtemp (°C)	Gpress (atm)	Syngas (kg/h)
1	200	0.8	300	1.5	178.983
2	800	0.8	1000	0.8	197.302
3	500	1.15	650	1.15	193.826
4	800	1.5	300	0.8	179.001
5	500	1.15	650	1.15	193.826
6	500	1.15	300	1.15	178.991
7	200	0.8	1000	0.8	197.302
8	800	0.8	300	1.5	178.983
9	500	1.15	650	1.15	193.826
10	200	0.8	300	0.8	179.001
11	500	1.15	650	1.15	193.826
12	200	1.5	300	0.8	176.486
13	500	0.8	650	1.15	193.826
14	800	0.8	300	0.8	195.789
15	800	0.8	1000	1.5	197.302
16	200	1.15	650	1.15	193.826
17	500	1.15	650	1.15	193.826
18	500	1.15	650	1.5	192.517
19	200	1.5	300	1.5	178.983
20	500	1.15	650	0.8	195.789
21	800	1.5	1000	1.5	197.302
22	800	1.15	650	1.15	193.826
23	500	1.15	1000	1.15	197.302
24	200	1.5	1000	1.5	197.302
25	500	1.5	650	1.15	193.826
26	200	1.5	1000	0.8	197.302
27	200	0.8	1000	1.5	197.302
28	800	1.5	1000	0.8	197.302
29	500	1.15	650	1.15	193.826
30	800	1.5	300	1.5	178.983

Analysis of Variance for Gasification of Fruit Waste

Table 7 presents the results of analysis of variance carried out on the gasification of mango endocarp. The model was representing the gasification process with probability error value (P-value) is 0.0001 which is less 5%, The probability error (P-value) less than 5 % indicated that the model is significant (Huan *et al.,* 2024). Also, this can be observed from the work of (Antung et al., 2024), their findings revealed that p-value 0.00089 which is even higher than p-value obtained from this work 0.000l for the overall model fitting. The independent variable decomposer and gasifier temperature and pressure, it can be observed from the Table 15 that only the p-value of gasifier temperature (0.0001) less than 5 %, this come term that in the gasification , the gasifier temperature is more significant , that is why (Aentung et al., 2024) did not consider pressure in their work. Furthermore, the coefficient of determination R^2 = 0.9458 which is very close to one, R^2 very close to unity indicate significance of model. Thus, the mathematical model developed from the design expert environment is quadratic in nature as depicted in Equation 2.

Table 7: Results of ANOVA RSM CCD Gasification of Food Waste

Sources	Sum of Squares	df	Mean Square	F-Value	P-Value	
Model	1613.35	14	115.24	18.70	< 0.0001	Significant
A-Dcomtemp	20.70	1	20.70	3.36	0.0867	
B-Dcompress	20.70	1	20.70	3.36	0.0867	
C-Gtempt	1258.70	1	1258.70	204.28	< 0.0001	
D-Gpress	17.25	1	17.25	2.80	0.1150	
AB	12.73	1	12.73	2.07	0.1711	
AC	23.29	1	23.29	3.78	0.0709	
AD	23.29	1	23.29	3.78	0.0709	
BC	23.29	1	23.29	3.78	0.0709	
BD	23.29	1	23.29	3.78	0.0709	
CD	12.87	1	12.87	2.09	0.1690	
A^2	0.0653	1	0.0653	0.0106	0.9194	
B^2	0.0654	1	0.0654	0.0106	0.9193	
C^2	78.96	1	78.96	12.82	0.0027	
D^2	0.6111	1	0.6111	0.0992	0.7572	
Residual	92.43	15	6.16			
Lack of Fit	92.43	10	9.24			Not significant
Pure Error	0.0000	5	0.0000			
Cor Total	1705.78	29				
R^2 = 0.9458 ; Adjusted R^2 = 0.8952; Predicted R^2 = 0.5543; Adeq Precision = 13.9116						

$$\text{Syngas} = +193.75 + 1.07A - 1.07B + 8.36C - 0.9789D - 0.8920AB - 1.21AC - 1.21AD + 1.21BC + 1.21BD + 0.8967CD + 0.1587A^2 + 0.1588B^2 - 5.52C^2 + 0.4857D^2 \quad \dots (2)$$

3.5.3 Effect of gasification process parameters interaction

The effect of the parameter interactions was carried out gain more insight on the gasification process, the gasifier and decomposer reactors temperatures and pressures.

3.5.3.1 Effect of decomposer reactor temperature and pressure

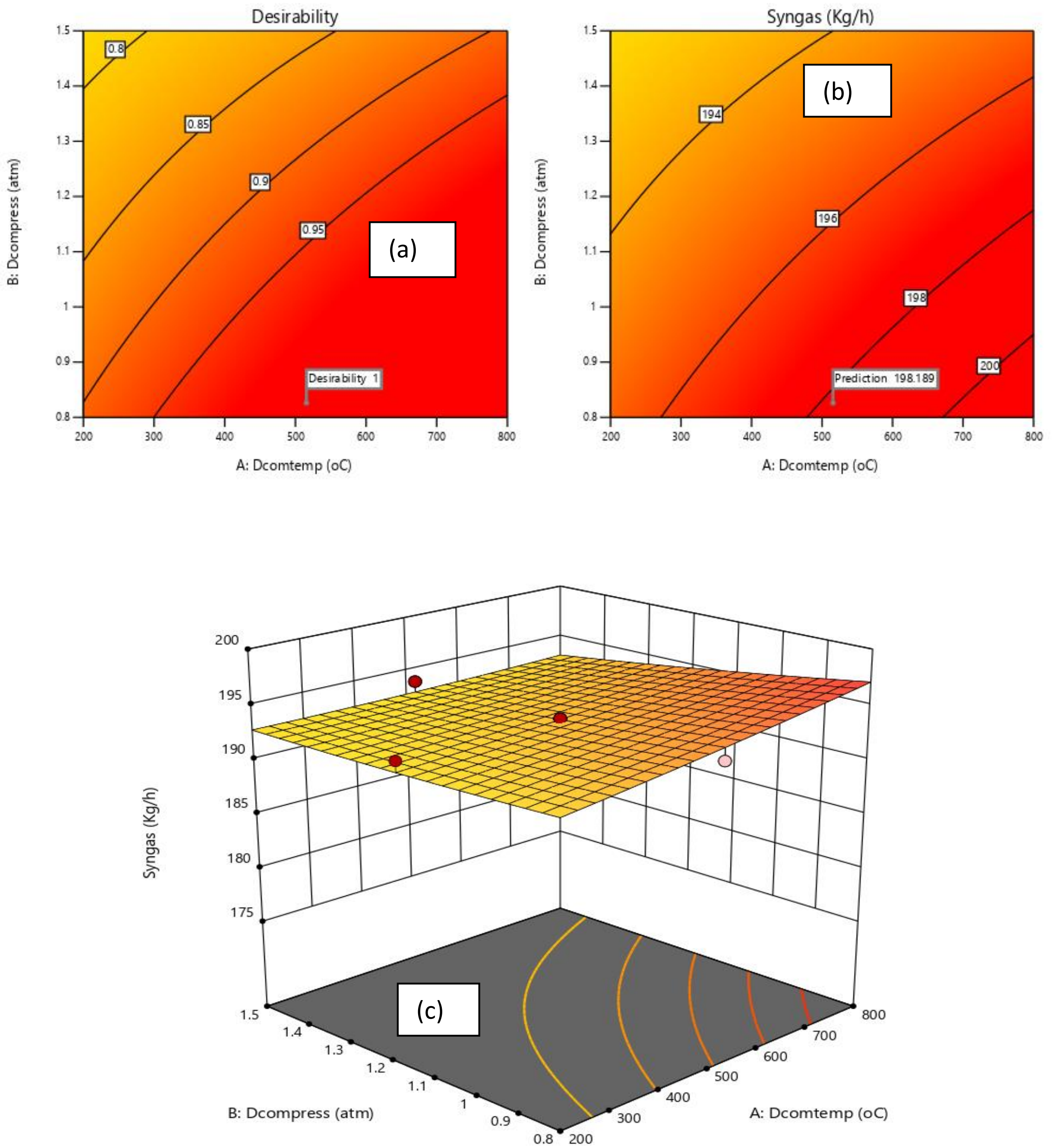

Figure 6: Effect of Decomposer Reactor Temperature and Pressure On (A) Contour Plot Desirability, (B) Contour Plot Syngas and (d) 3D plot

3.5.3.2 Effect of gasifier reactor temperature and pressure

Figures 7 (a,b and c) present the results of interaction of decomposer reactor temperature and pressure on the amount of syngas produced. It can be observed from the Figures that the predicted highest amount of syngas is 198.1898698 kg/h at temperature, pressure and desirability of 650 °C, 1.15 atm and 1 respectively.

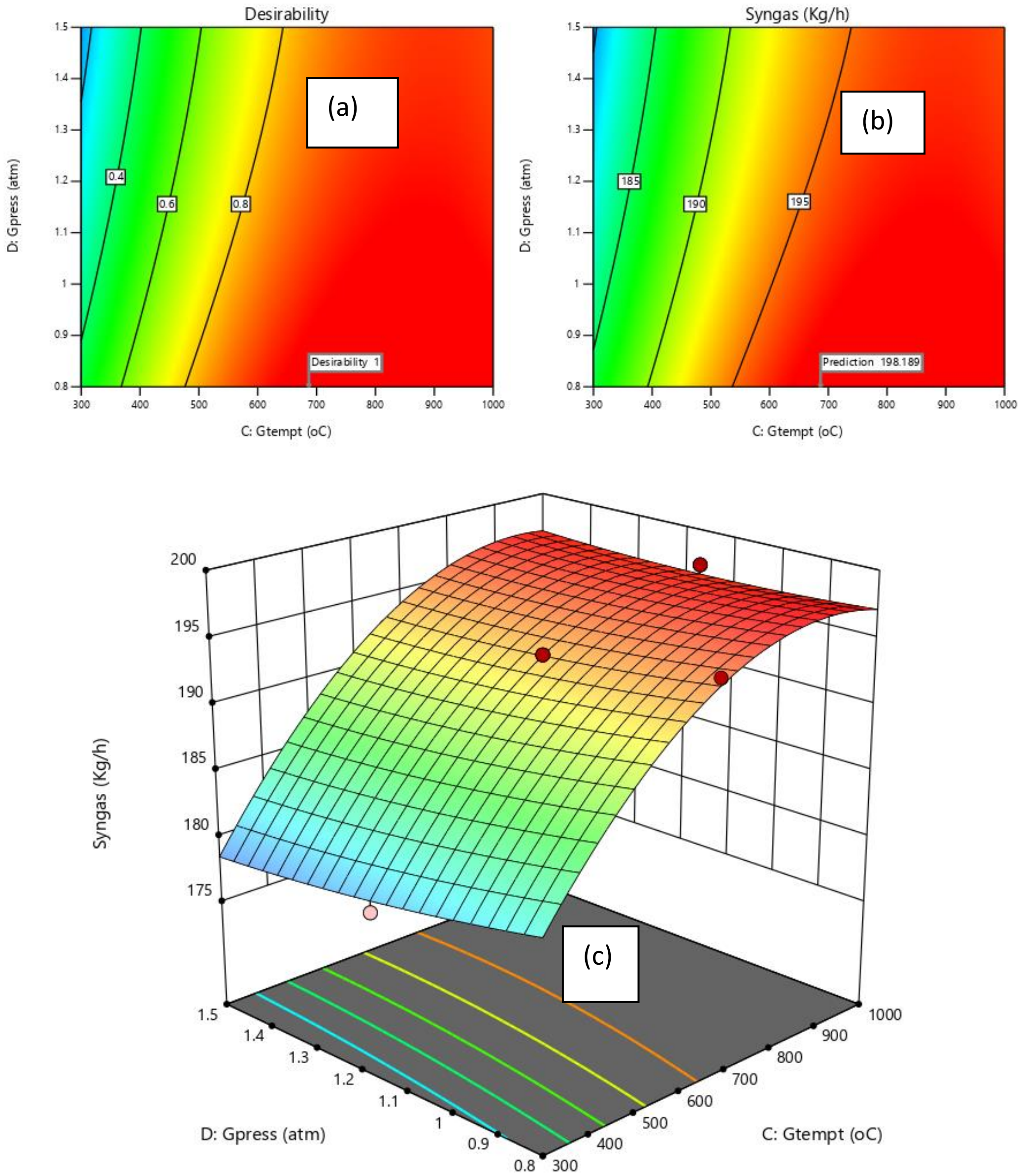

Figure 7: Effect of Gasifier Reactor Temperature and Pressure On (A) Contour Plot Desirability, (B) Contour Plot Syngas and (d) 3D plot

Optimization Result for Gasification

Table 8 depicted the optimum results predicted by the response surface methodology central composite design using design expert. The results obtained from this research work was almost similar to the results from work of Waheed et al., (2024), 196.50 kg/h of syngas yield was reported.

Table 8: Results of Optimization of Gasification Process

Method	Dtemperature (℃)	Dpressure (atm)	Gtemperature (℃)	Gpressure (atm)	Syngas (Kg/h)	Desirability
Optimization	610.303	1.081	841.284	1.012	197.534	1

CONCLUSION

A sustainable energy source that supports carbon neutrality must be found by researchers in order to meet both the growing energy demand and the worrying deterioration in climate conditions. There are significant amounts of fruit waste, especially in tropical and subtropical areas, that are promising for the production of bioenergy. This research presents process simulation model in Aspen Plus and optimization of hydrothermal gasification and pyrolysis of fruit waste biomass from bananas, oranges, mango and water melon for syngas production.

The result of the gasification show mango endocarp have the highest amount of syngas (197.302 kg/h) followed by the other fruits in the order water melon peel, orange peel and banana peel as 195.38, 193.386, and 148.09 kg/h respectively. Pyrolysis of banana peel gave the highest amount of syngas 93.478 kg/h compare to pyrolysis of mango endocarp, water melon peel and orange peel with syngas yield of 91.18, 89.07, and 87.013 kg/h respectively.

The model was representing the gasification process with P-value of 0.0001 which is less than 5%, indicated that the model is significant. The gasifier temperature is most significant parameter and the coefficient of determination R^2 is 0.9458 which is very close to one. The optimum operating parameters for syngas yield at 197.534 kg/h at decomposer temperature, decomposer pressure, gasifier temperature, gasifier pressure and desirability of 610 °C, 1.081 atm, 841 °C, 1.012 atm and 1 respectively.

It can be concluded that mango endocarp produced the greatest amount of syngas by steam gasification methods. This further demonstrated the mango endocarp has a potential as a vigorous gasification candidate for syngas production.

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