

Effects of selected process parameters on product yields from pyrolysis of sweet potato stems

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Abstract

The increasing demand for sustainable energy sources has driven interest in converting agricultural residues into renewable biofuels. This study investigated the effects of selected process parameters on product yields from the pyrolysis of sweet potato stems, an abundant agro-waste material. A fixed-bed reactor was used to examine the influence of temperature and residence time on biofuel yields. Experimental design and optimization were performed using Design Expert 12.0.1.0 software, with pyrolysis temperatures ranging from 350 °C to 550 °C and residence times between 10 min and 30 min. Analysis of variance (ANOVA) indicated that both parameters significantly affected the product yields ($p = 0.0001$). The optimal condition was achieved at 500 °C and 30 min, yielding a maximum bio-oil output of 29.50 wt%. The produced bio-oil exhibited favorable fuel properties with 54.85% carbon and 21.12% hydrogen contents. Proximate and ultimate analyses of the feedstock revealed a low ash content (0.06 %), high volatile matter (85 %), and substantial carbon composition (47.10 %), underscoring its potential as a biofuel precursor. The findings establish sweet potato stem as a promising and sustainable feedstock for biofuel production, contributing to efficient agricultural waste management and renewable energy generation. Future studies should focus on upgrading and characterizing the derived bio-oil for engine applications.

Keywords: Pyrolysis; Sweet Potato Stem; Bio-Fuel; Bio-Oil; Agricultural Residues; Renewable Energy; Waste Management

1. Introduction

Energy plays a vital role in the development of any nation, and the challenges associated with energy supply are often described under the broad concept of an “energy crisis.” This term may refer to electricity shortages, depletion or imbalance in the utilization of natural resources such as coal, oil, and gas, or the rising gap between demand and supply. Addressing these challenges requires exploring alternative energy sources that are both affordable and locally available (Roberta et al., 2020). One effective approach is not only to conserve existing energy resources but also to efficiently harness renewable sources of energy (Bridgwater, 2012).

The global transition towards renewable energy has increased interest in biomass as a sustainable feedstock for energy and chemical production. Biomass is a versatile renewable resource that can be thermochemically converted into secondary energy carriers such as bio-char, bio-oil, and bio-gas (Bridgwater, 2012). Among the various conversion

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technologies, pyrolysis has attracted considerable attention due to its efficiency and potential to transform agricultural residues into high-value energy products.

Pyrolysis is a thermochemical decomposition process that occurs in the absence of oxygen, producing a spectrum of products including bio-char, bio-oil, and bio-gas (Bridgwater, 2012). The yield and quality of these products depend on key process parameters such as temperature, heating rate, particle size, feedstock, and residence time. Of these, temperature and residence time are particularly significant in determining both the quantity and composition of pyrolysis products (Thorsell et al., 2004). For instance, stem tubers such as sweet potato stems, due to their high starch and lignocellulosic content, typically yield bio-oil rich in carbohydrates and oxygenated compounds (Tipeng *et al.*, 2015).

The pyrolysis of sweet potato stems offers a promising pathway for renewable energy generation while contributing to waste valorization and environmental sustainability. Optimizing pyrolysis conditions is essential, as temperature strongly influences the product distribution: higher temperatures tend to enhance bio-gas yields, whereas moderate temperatures favor bio-oil production (Itabiya et al., 2016). Consequently, systematic investigations of process parameters such as temperature and residence time are crucial to improving the efficiency of biomass-to-energy conversion and reducing dependence on fossil fuels (Roberta et al., 2020). Sangotayo et al. [13] investigated the characterization of activated carbon produced from local agricultural materials such as coconut shells, coconut husks, maize husks, and palm kernel shells. Results showed that the mass and adsorption capacity of the locally produced activated carbons were higher than those of imported ones. The study suggested that utilizing locally available agricultural residues for pyrolysis is essential for sustainable resource management. Building on this foundation, the present research investigated the influence of temperature and time on biofuel yields from the pyrolysis of sweet potato stems.

2. Materials and Method

2.1. Feedstock Processing and Characterization

Sweet potato stem residues were sourced following a survey to identify suitable collection sites. Olugbemi Village, located in Surulere Local Government Area, Ogbomoso, Oyo State, Nigeria, has been selected due to its extensive agricultural activities and the availability of the crop. **The feedstock was sun dried for 8 days to reduce its moisture content**, weighed, and sealed in airtight bags to prevent reabsorption of moisture, then stored at room temperature before pyrolysis experiments. Proximate analysis was conducted to determine the feedstock moisture content, volatile matter, ash content, and fixed carbon content. Moisture content, volatile matter, and ash content were evaluated following ASTM E871 (2019) standards. Fixed carbon content was calculated using the formula:

$$\%FC = 100 - (C + AC + VC) \quad (1)$$

The elemental composition of sweet potato was analyzed using titration and gravimetric methods. Sulfur content was measured with a spectrometer, while oxygen content was calculated by summing the percentages of total carbon, nitrogen, and sulfur and subtracting the total from 100:

$$\%oxygen = 100 - (\% of C + N + S) \quad (2)$$

2.2. Experimental Setup and Procedure

Pyrolysis of sweet potato stems was carried out in a fixed-bed pyrolysis system consisting of a retort, condensate receiver, and gas collection unit, all fabricated from mild steel (Figure 1) show schematic diagram of pyrolysis unit. The feedstock (Figure 2) was introduced into the reactor, with 100 g of sweet potato stems loaded into the retort for each experimental run in accordance with the parameters generated by Design Expert Version 12.0.0.

The system was tightly sealed using bolts, nuts, and a gasket to prevent gas leakage, after which the retort was placed in a clay-brick-lined electric furnace. Pyrolysis was conducted by varying the operating temperature between 350 and 550 °C at intervals of 50 °C, while residence times were adjusted between 10 and 30 minutes at 5-minute intervals.

During the process, the retort was linked to the condensate receiver through an insulated galvanized pipe. Initially, the condensate receiver valves were kept closed to enable condensation of a significant portion of the gases into liquid. Once this was achieved, the valve was opened to direct uncondensed gases into the gas collection unit.

At the end of the specified residence time, the pyrolysis process was terminated. The resulting bio-char was retrieved from the retort, cooled to room temperature, and weighed using an Ohaus top-loading balance. Finally, the yields of bio-char, bio-oil, and bio-gas were determined as percentages of the initial feedstock weight using equations (3), (4), and (5).

$$\%Bio - char\ yield = \frac{mass\ of\ the\ char\ obtained}{mass\ of\ the\ raw\ sample} \times 100 \quad (3)$$

$$\%Bio - liquid\ yield = \frac{mass\ of\ the\ liquid\ obtained}{mass\ of\ the\ raw\ sample} \times 100 \quad (4)$$

$$\%Bio - gas\ yield = 100 - (\%Bio - char\ yield + \%Bio - oil\ yield) \quad (5)$$

As specified in the experimental design, the procedure was repeated for all samples under different pyrolysis temperatures and residence times. The conditions that produced the maximum bio-oil yield were identified and recorded for subsequent analysis and evaluation

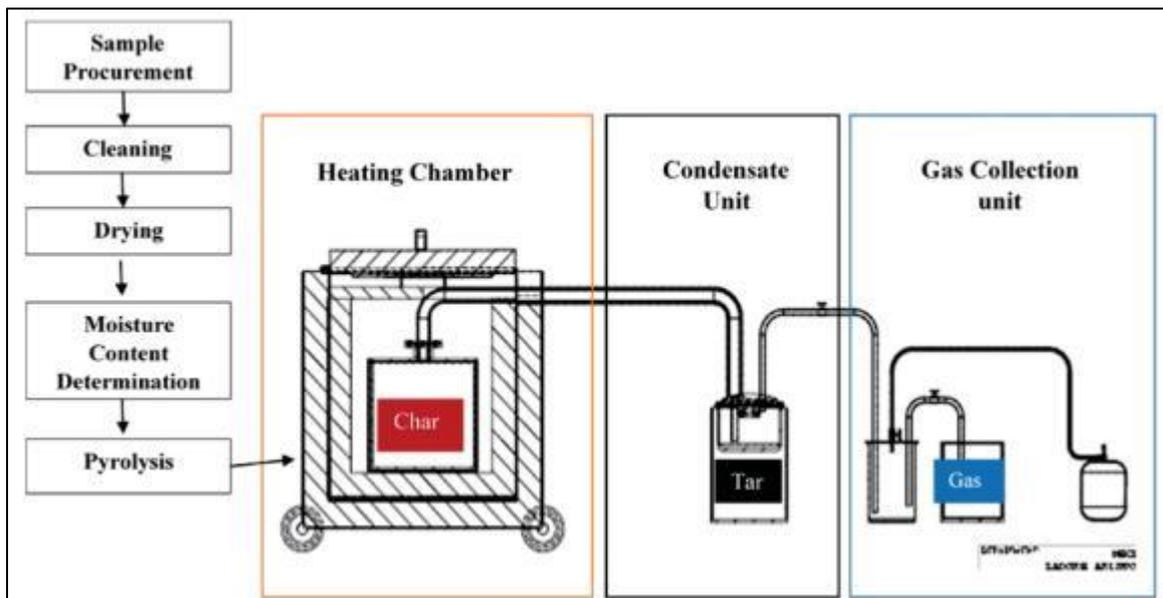


Figure 1 Schematic Diagram of Pyrolysis Unit



Figure 2 Sweet Potato stem

The elemental composition of the bio-oil was analyzed using a CHONS Elemental Analyzer, while sulfur content was specifically measured with a spectrophotometer. Oxygen content was determined indirectly by summing the percentages of carbon, hydrogen, nitrogen, and sulfur, and subtracting the total from 100, as expressed in Equation (2).

In addition, the performance of the pyrolysis yields was assessed using the Signal-to-Noise Ratio (SNR), a statistical metric that evaluates the ratio of the desired signal to background noise. A higher SNR indicates better efficiency of pyrolysis products. The SNR values were calculated using Equation (6), following the method of Başar et al. (2022).

$$SNR = -10 \log \left[\frac{1}{n} \sum_{i=1}^n \frac{1}{y_i^2} \right] \times 100 \quad (6)$$

The yield percentage (y_i) of each pyrolysis product was calculated using Equations (3), (4), and (5), where n represents the total number of experimental runs.

3. Results and Discussion

3.1. Physicochemical Composition of Raw Sweet potato stems

The proximate composition of sweet potato stem is presented in Table 1. The moisture content was 6.85%, which is within the acceptable range for pyrolysis feedstocks (<10%). This value is higher than the 2.98% reported for sweet potato vine by (Wang et al., 2015), but still suitable since low moisture content enhances thermal efficiency by reducing the energy required for water vaporization (Bridgwater, 2012; Adeleke et al., 2019).

The ash content was very low at 0.06%, which is advantageous compared to other biomass residues such as broom weed (9.83%) reported by (Adewumi et al., 2023) and cowpea bean pod (4.38%) reported by (Roberta et al., 2020). Low ash content minimizes fouling and slagging tendencies, thereby improving the heating efficiency of the feedstock (Pehlivan et al., 2023).

The volatile matter content of sweet potato stem was 86.40%, higher than the 79.73% reported for sweet potato vine (Wang et al., 2015). High volatile matter indicates that the material is rich in volatile organic compounds, which favor higher yields of bio-oil and bio-gas during pyrolysis (Roberta et al., 2020). Finally, the fixed carbon content was 6.69%,

suggesting a moderate potential for char formation. This balance between volatile matter and fixed carbon makes sweet potato stem a promising feedstock for bio-fuel production.

Table 1 Result of physical and chemical composition of sweet potato stem

Materials	Properties	Unit	Value
Sweet Potato	Moisture content	%	6.85
	Volatile content	%	86.40
	Ash content	%	0.06
	Fixed Carbon Content	%	6.69

The ultimate analysis of sweet potato stem is summarized in Table 2. The carbon content was 47.10%, which is higher than the 45.44% reported for elephant grass (Efetobor *et al.*, 2015), suggesting a high proportion of combustible matter and good energy potential. The hydrogen content was 6.23%, slightly higher than the 5.59% reported for elephant grass (Efetobor *et al.*, 2015). A relatively high hydrogen level indicates improved reactivity during pyrolysis and contributes to the production of combustible gases such as water gas.

The nitrogen content was low at 1.02%, comparable to values reported for other biomass residues such as broom weed (0.52%) (Adewumi *et al.*, 2023). Low nitrogen content is desirable because it minimizes nitrogen oxide emissions, thereby supporting cleaner energy production. The sulphur content was 0.12%, which is lower than the 0.35% reported for elephant grass (Efetobor *et al.*, 2015). This very low sulphur value reduces the risk of sulfur dioxide emissions, enhancing the environmental sustainability of the feedstock (Shariff *et al.*, 2016).

The oxygen content was 45.53%, higher than the 31.03% and 40.95% reported for broom weed by Adewumi *et al.* (2023) and (Efetobor *et al.*, 2015), respectively. High oxygen content indicates good combustibility, favoring energy release during conversion.

The lignocellulosic composition of sweet potato stem consist of 28.95% cellulose, 17.60% hemicellulose, and 22.15% lignin. The relatively high cellulose fraction supports enhanced bio-oil yield during pyrolysis, while moderate lignin levels contribute to char formation. The higher heating value (HHV) was 21.78 MJ/kg, slightly higher than many comparable agricultural residues, indicating good potential for energy generation.

Table 2 Ultimate Composition of Sweet Potato Stem

Materials	Properties	Unit	Value
Sweet Potato	Carbon content	%	47.10
	Oxygen content	%	45.53
	Hydrogen content	%	6.23
	Nitrogen content	%	1.02
	Sulphur content	%	0.12
Lignocellulose	Cellulose	%	28.95
	Hemicellulose	%	17.60
	Lignin	%	22.15
Higher Heating value	Higher Heating value	MJ/KG	21.78

Table 3 Analysis of Variance (ANOVA) For the Product Yields from Sweet Potato stems

Response	Source	Sum of Squares	Degree of freedom	Mean Square	F-value	p-value
Bio-Char (%)	Model	2169.94	8	271.24	724.33	< 0.0001
	A	2105.87	4	526.47	1405.89	< 0.0001
	B	64.07	4	16.02	42.78	< 0.0001
	Residual	5.99	16	0.3745		
	Cor Total	2175.93	24			
Bio-Oil (%)	Model	572.00	8	71.50	63.01	< 0.0001
	A	522.68	4	130.67	115.16	< 0.0001
	B	49.32	4	12.33	10.87	0.0002
	Residual	18.16	16	1.13		
	Cor Total	590.15	24			
Bio-Gas (%)	Model	1023.17	8	255.79	257.88	< 0.0001
	A	1023.17	4	255.79	257.88	< 0.0001
	B	19.84	4	0.9919	60	0.0002
	Residual	1043.01	16			
	Cor Total	1023.17	24			

A = Temperature (°C), B = Time (min.)

Table 4 Model comparison statistics of product yield (bio-char, bio-oil, and bio-gas) from sweet potato stem

	Bio- Char Yield		
Standard Deviation	0.6119	R ²	0.9972
Mean	27.86	Adjusted R ²	0.9959
C.V. %	2.20	Predicted R ²	0.9933
		Adeq Precision	80.0021

	Bio -Oil Yield		
Standard Deviation	1.07	R ²	0.9692
Mean	22.67	Adjusted R ²	0.9539
C.V. %	4.70	Predicted R ²	0.9249
		Adeq Precision	27.6435

	Bio- Gas Yield		
Standard Deviation	0.9959	R ²	0.9810
Mean	49.44	Adjusted R ²	0.9772
C.V. %	2.01	Predicted R ²	0.9703
		Adeq Precision	39.2503

3.2. Statistical Analysis Models

3.2.1. Sweet Potato

The linear equation obtained from the regression analysis of bio-char, bio-oil and bio-gas in term of coded value were presented in equation (7), (8) and (9).

$$Y = 27.8592 + 12.4408A_1 + 7.1848A_2 + 0.5108A_3 - 7.6412A_4 + 2.6208B_1 + 0.9368B_2 - 0.5152B_3 - 1.2252B_4 \tag{7}$$

$$Y = 22.6716 - 7.7196A_1 - 1.4756A_2 + 2.4724A_3 + 6.0124A_4 - 2.6616B_1 - 0.0276B_2 + 0.9844B_3 + 0.4304B_4 \tag{8}$$

$$Y = 49.12 - 3.20A_1 - 3.82A_2 - 2.62A_3 + 0.816A_4 - 1.70B_1 - 0.904B_2 - 0.084B_3 + 0.896B_4 \tag{9}$$

Where Y represents the predicted response, and A₁-A₄ and B₁-B₄ are the coded levels of factors A and B, respectively.

The ANOVA results for bio-char, bio-oil, and bio-gas yields confirmed that the selected factorial models were statistically significant (p < 0.0001) as shown in Table 3. The very high F-value with a negligible error term indicates excellent agreement between predicted and experimental values. Both temperature (A) and residence time (B) were identified as significant factors, strongly influencing product formation. In both cases, temperature and residence time had p-values < 0.05, confirming their importance in determining product distribution at 95% confidence level. The relatively low residual errors across all models further emphasize their robustness.

The results demonstrated that temperature and residence time are the dominant process parameters governing the yields of bio-char, bio-oil, and bio-gas, and the developed models provide strong predictive capability for navigating the design space.

The statistical parameters obtained from the ANOVA, presented in Table 4, confirmed the accuracy of the developed models. For bio-char yield, the model exhibited a high coefficient of determination (R² = 0.9972) and a low coefficient of variation (C.V. = 2.20), indicating excellent agreement between experimental and predicted values. The bio-oil yield model achieved an R² of 0.9692 with a C.V. of 4.70, while the bio-gas yield model recorded an R² of 0.9810 and a C.V. of 2.01.

Evidence of model adequacy was provided by the adjusted R², predicted R², and adequate precision values. The Signal-to-Noise Ratios (SNR) were 80.0021 for bio-char, 27.6435 for bio-oil, and 39.2503 for bio-gas. Since all SNR values exceeded the minimum desirable threshold of 4, the models were confirmed to be highly suitable for navigating the design space.

Table 5 presents the design matrix for the pyrolysis experiment, showing temperature and residence time as the process factors and product yields (bio-char, bio-oil, and bio-gas) as the responses.

Table 5 Design Matrix of Sweet Potato Stems using Temperature and Time as Independent factors and the Product yield as Dependent factors Response

Runs	A	B	Bc	Bo	Bg
1	400	30	32.70	23.60	43.70
2	350	20	40.00	15.10	44.90
3	400	20	34.92	21.78	43.30
4	500	10	23.20	26.00	50.08
5	550	25	13.90	23.80	62.30
6	400	25	33.70	22.10	44.20
7	450	25	26.85	25.00	48.15

8	450	20	27.50	26.90	45.60
9	450	10	30.00	23.50	46.50
10	400	15	36.50	20.20	43.33
11	550	10	18.50	20.10	61.40
12	500	25	19.52	28.10	52.28
13	500	15	20.48	29.32	50.20
14	500	30	18.31	29.50	52.19
15	550	15	16.50	23.50	60.00
16	400	10	37.40	18.30	44.33
17	350	25	39.20	16.51	44.29
18	350	30	38.00	17.00	45.00
19	550	30	13.20	25.51	61.29
20	450	15	29.50	26.20	44.33
21	500	20	19.58	30.50	49.92
22	550	20	14.72	24.00	61.28
23	450	30	28.00	24.12	47.88
24	350	15	41.00	14.00	45.00
25	350	10	43.30	12.15	44.55

A = Temperature (°C) B = Time (min.) Bo = Bio-oil yield from Sweet potato stem (wt.%); Bc = Bio-Char yield from Sweet potato stem (wt.%) Bg = Bio-gas yield from Sweet potato stem (wt.%).

3.3. Effect of Pyrolysis Parameters on the Product Yields

3.3.1. Sweet Potato

Figure 3 illustrates the three-dimensional response surfaces and contour plots of sweet potato stem pyrolysis, showing the combined influence of temperature and residence time on bio-char, bio-oil, and bio-gas yields. The results indicate that bio-char yield decreases progressively with increasing pyrolysis temperature, which is consistent with established pyrolysis behavior. The highest bio-char yield of 43.30% was recorded at 350 °C with a residence time of 10 minutes, as shown in Figure 3(a). This agrees with the findings of Tipeng et al. (2015), who reported that elevated temperatures lead to reduced bio-char production due to intensified thermal decomposition.

As shown in Figure 3(b), bio-oil yield increased with temperature up to 500 °C, after which it declined at 550 °C. The maximum bio-oil yield of 29.50% was obtained at 500 °C and a residence time of 30 minutes, as presented in Table 5. In contrast, bio-gas yield increased steadily with both temperature and residence time, reaching a peak value of 62.30% at 550 °C and 25 minutes, as depicted in Figure 3(c).

These results are consistent with earlier studies by Itabiya et al. (2016) and Adewumi et al. (2023), which similarly reported that higher temperatures enhance bio-oil and bio-gas yields while reducing bio-char production.

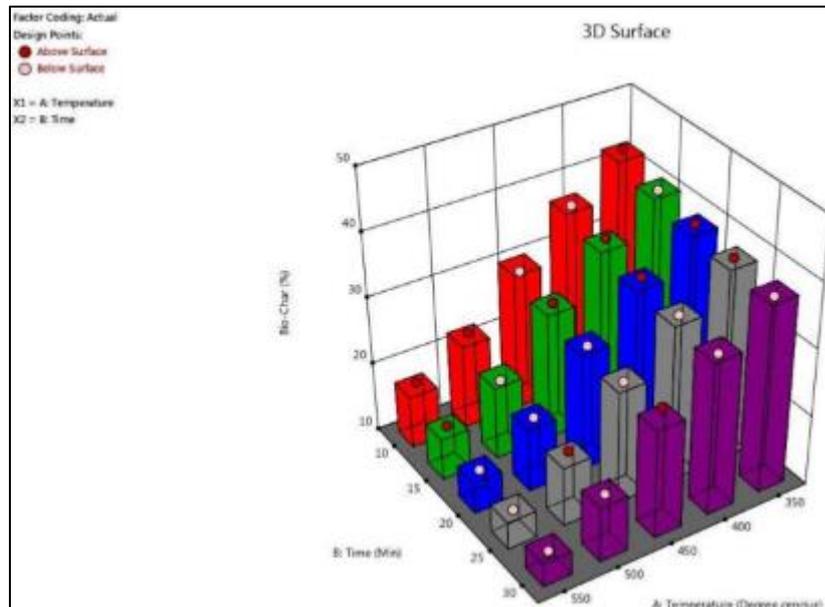


Figure 3(a) Contour Plots of Sweet Potato Stem Pyrolysis at at 350 °C

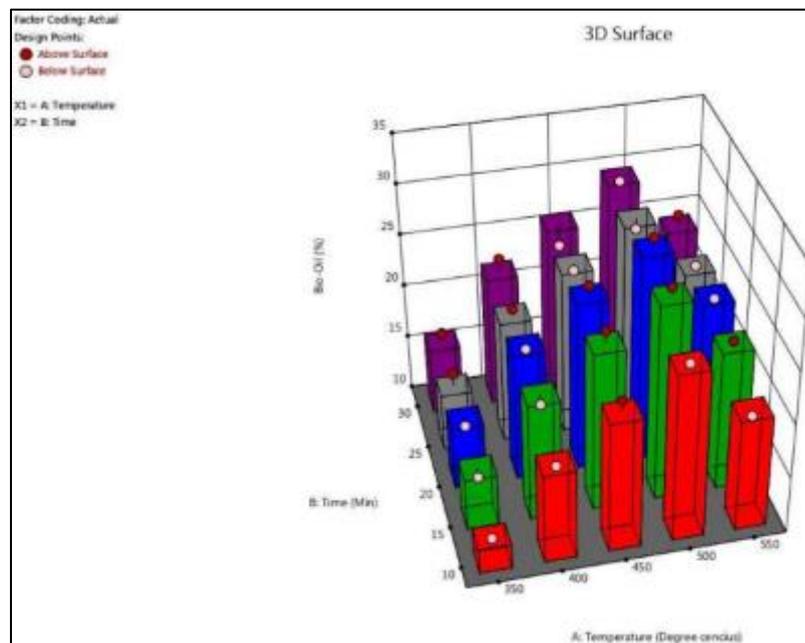


Figure 3(b) Contour Plots of Sweet Potato Stem Pyrolysis at 500 °C

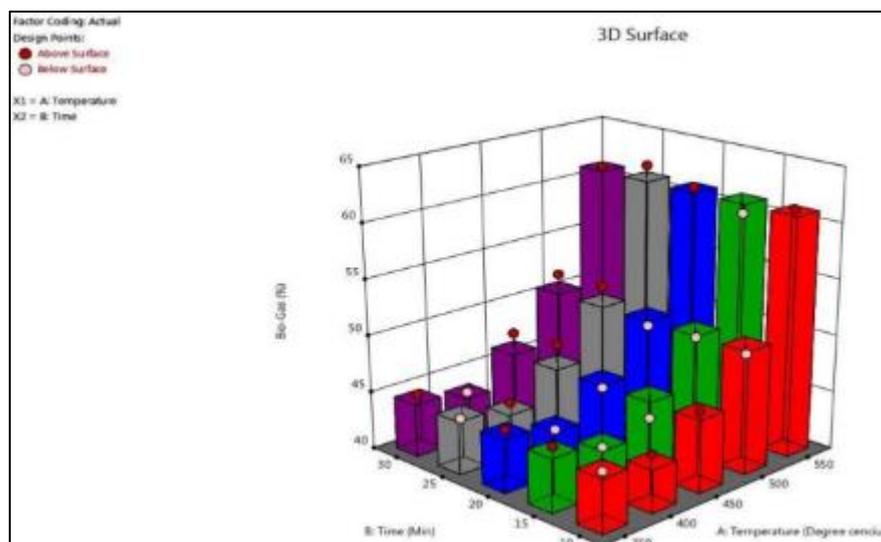


Figure 3(c) Contour Plots of Sweet Potato Stem Pyrolysis at 550 °C

4. Conclusion

This study investigated the influence of process parameters on product yields from the pyrolysis of sweet potato stem. The physicochemical characterization showed that sweet potato stem is a promising feedstock due to its high carbon (47.10%) and hydrogen (6.23%) contents, elevated volatile matter (86.40%), low ash content (0.06%), and relatively high heating value (21.78 MJ/kg), all of which enhance its energy potential and thermal efficiency.

The results demonstrated that pyrolysis temperature and residence time strongly affected product distribution. Increasing temperature and prolonging residence time reduced bio-char yield while favoring bio-gas production. The highest bio-oil yield from sweet potato stem (30.5%) was obtained at 500 °C and 30 minutes, indicating that moderate to high temperatures with sufficient residence time are optimal for maximizing liquid fuel recovery. Sweet potato stem has been established as a viable biomass resource for bio-oil production, highlighting its potential contribution to renewable energy development. By adopting appropriate conversion technologies, sweet potato stem can be converted into medium grade bio-oil products suitable for both domestic and industrial applications. This utilization not only reduces waste and associated environmental challenges but also supports the transition toward cleaner and more sustainable energy alternatives.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article

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