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EXPLORING THE ENERGY GENERATION POTENTIAL OF JATROPHA CAKE IN A BIOREFINERY: AN OPTIMIZATION STUDY

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Abstract. Waste management and energy access remain critical challenges globally, especially in developing countries where poor waste management and unreliable power supply exacerbate environmental and socio-economic issues. This study aims to explore the potential of using Jatropha cake as a sustainable bioenergy source in gas-turbine power plants to address these challenges. Using a Central Composite Design (CCD) approach, the study evaluates the effects of compressor efficiency, turbine efficiency, heat transfer coefficients, and heat transfer area on power generation from Jatropha cake, modeled using the DWSim simulation package. The findings show that an open-loop gas-turbine configuration with a compressor efficiency of 83.92% and turbine efficiency of 98% can generate a maximum power output of 174235 kW. In contrast, the closed-loop configuration, optimized with a heat exchanger (HX) at 120 W/m²K heat transfer coefficient and 1000 m² heat transfer area, yields 74375.70 kW. The results suggest that the open-loop configuration is more efficient, offering significantly higher power generation. This study highlights the viability of Jatropha cake as a bioenergy resource, providing a promising solution for improving power supply in energy-deficient communities while contributing to sustainable waste management practices.

Keywords: *Biomass, Bioenergy, Biorefinery, Jatropha, Alternative Energy, Environment.*

Rezumat. Gestionarea deșeurilor și accesul la energie rămân provocări critice la nivel global, în special în țările în curs de dezvoltare, unde gestionarea deficitară a deșeurilor și alimentarea cu energie electrică nesigură amplifică problemele de mediu și socio-economice. Acest studiu își propune să exploreze potențialul utilizării turtei de Jatropha ca sursă durabilă de bioenergie în centralele electrice cu turbine pe gaz pentru a aborda aceste provocări. Folosind o abordare de tip Central Composite Design (CCD), studiul evaluează efectele eficienței compresorului, eficienței turbinei, coeficienților de transfer de căldură și suprafeței de transfer de căldură asupra generării de energie din turta de Jatropha, modelată folosind pachetul de simulare DWSim. Rezultatele arată că o configurație cu turbină pe gaz în buclă deschisă, cu o eficiență a compresorului de 83,92% și o eficiență a turbinei de 98%, poate genera o putere maximă de 174235 kW. În schimb, configurația în buclă închisă, optimizată cu un schimbător de căldură (HX) la un coeficient de transfer de căldură de 120 W/m²K și o suprafață de transfer de căldură de 1000 m², produce 74375,70 kW. Rezultatele sugerează că configurația în buclă deschisă este mai eficientă, oferind o generare de energie semnificativ mai mare. Acest studiu evidențiază viabilitatea turtei de Jatropha ca resursă bioenergetică, oferind o soluție promițătoare pentru îmbunătățirea alimentării cu energie în comunitățile cu deficit energetic, contribuind în același timp la practici durabile de gestionare a deșeurilor.

Cuvinte cheie: *Biomasă, Bioenergie, Biorafinărie, Jatropha, Energie alternativă, Mediu.*

1. Introduction

Waste management has continued to be a subject of concern across the globe, irrespective of a country's classification, whether developed, developing, or underdeveloped [1–6]. The issue continues to attract attention toward finding better approaches for minimizing waste or transforming waste into valuable products or applications, such as biofuels, bio-based chemicals, or bioenergy development.

Many research efforts have focused on exploring measures for adding value to waste globally generated across communities [1,5,7]. Literature reports indicate a continuous trend of rising waste generation [2], suggesting that more attention should be given to research exploring initiatives for transforming waste into valuable chemicals and energy, which is vital.

Most developing countries that also suffer from poor waste management are also faced with inconsistent and interrupted power supply from their governments [2,8-12]. A large number of residents in such communities rely on locally generated power through solar power technology or resort to the use of biomass energy (i.e., firewood burning), which is environmentally unfriendly [2]. As a result, the significance of exploring the potential for bioenergy generation from waste in such communities would go a long way in addressing the energy supply problems they face. Some studies in the literature have explored the potential of transforming bagasse [9,13], sawdust [14,15], maize cob [16], and many other biomass sources for bioenergy generation in these communities. The literature indicates that these explorations have resulted in significant useful power generation [9,17–23]. However, attempts to explore the use of Jatropha cake in the literature are limited, and its application in running a power plant using either an open- or closed-loop gas-turbine power plant configuration has not yet been fully explored.

Hence, this study provides computational insight into the potential of using Jatropha cake for power generation, with optimization of the power generation capacity using both open- and closed-loop gas-turbine power plants. The study employs a process modeling and simulation approach, using an open-source process simulator (DWSim package). The findings reveal the achievable power generation capacity using Jatropha cake and the implications of compressor and turbine efficiency, including heat exchanger heat transfer area and coefficient, on the turbine feed stream temperatures and overall power generation capacity.

2. Materials and Methods

2.1. Computational details and Strategy

This research employed the use of DWSim [24] simulator in the modeling and simulation of the process of energy generation from Jatropha cake. In the study, it was resolved to use of the chosen simulator (DWSim) [25], since it was free and requires no need to purchase license. The Peng Robinson model [26] was chosen as the thermodynamic package for determination of accurate physical and transport properties and phase behavior. For the simulation of process plant, the stage-wise procedure shown in Figure 1 was adopted.

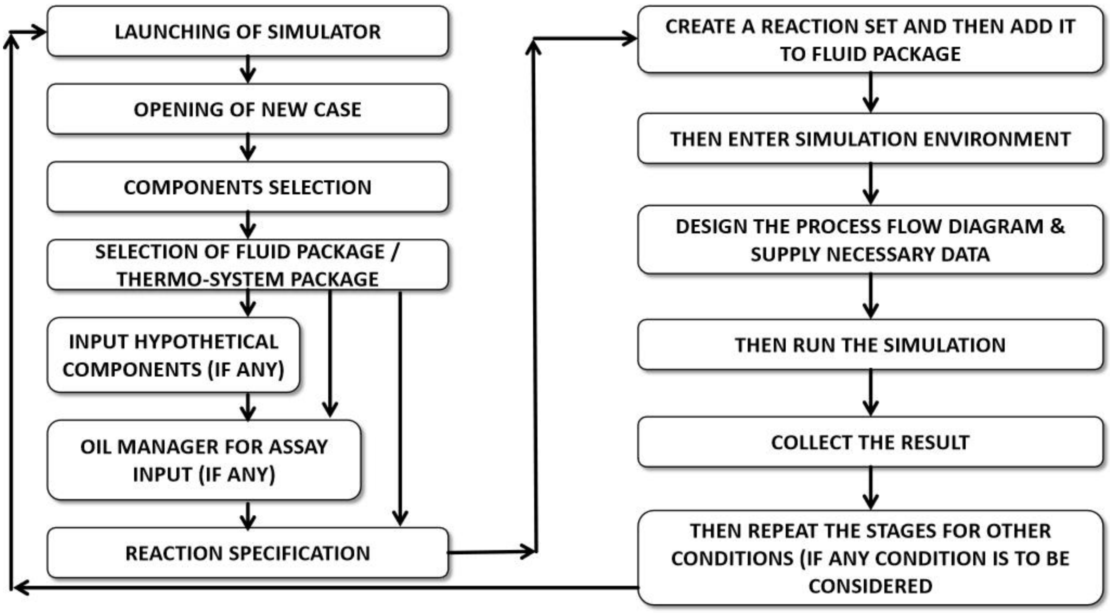


Figure 1. Flow Chart for Process Simulation (adopted from [27]).

In the modeling of the power plant, the study employs the use of the chemical composition data reported in the literature to model the Jatropha cake as the feedstock for the power generation process. However, in the study, the presence of the extractives was neglected (that is, approximated to be zero per cent weight) due to their insignificant percentage by weight reported and their volatility in the presence of high temperature. In a nutshell, the modeled values were normalized (in absence of percent for extractives) to 100%. These compositions are presented in Table 1.

Table 1

Jatropha cake composition

Component	Composition in % weight		
	Literature [28] Value	**Simulation Modeled Value**	**Normalized Value**
Cellulose	53.50	53.50	56.30
Hemicellulose	16.60	16.60	17.50
Lignin	24.90	24.90	26.20
Extractives	5.00	0.00	0.00

Table 2 presents the components selected from the DWSim compound database and those not available on the database (hypothetical compounds). The hypothetical compounds are created using their various properties such as their normal boiling points, molecular weights, molecular formulas and many other data gotten from literature [27].

Table 2

Hypothetical compounds and their properties

Compound	Specified Properties
Cellulose	Chemical Formula: $(C_6H_{10}O_5)_n$ where n = 100 units Molecular Weight$^{(E)}$,
Hemicellulose	Chemical Formula: $(C_5H_8O_4)_n$ where n = 10 units Molecular Weight$^{(E)}$
Lignin	Chemical Formula: $(C_{31}H_{34}O_{11})_n$ where n = 10 units Molecular Weight$^{(E)}$,

Note: E - estimated property.

Table 3

Components involved in the simulation process

Compound	Chemical formula	CAS number	Process application
Oxygen	O_2	7782-44-7	Combustor inlet
Carbon dioxide	CO_2	124-38-9	Combustor outlet
Water	H_2O	7732-18-5	Combustor outlet
Cellulose	$(C_6H_{10}O_5)_n$	9004-34-6	Feedstock
Hemicellulose	$(C_5H_8O_4)_n$	9014-63-5	Feedstock
Lignin	$(C_{31}H_{34}O_{11})_n$	9005-53-2	Feedstock

Note: CASnumber – Chemical Abstracts Service number.

The modeling of these compounds was done using the compound creator study option. Table 3 gives a summary of the modeled hypothetical compounds and properties inputted while modelling the compounds.

Table 4

Equipment used for modeling the open loop power plant

Equipment	Model	Operating condition
Air compressor	Compressor	Pressure ratio: 9.5, efficiency of 95%
Combustor	Mixer	Pressure calculation: maximum inlet
	Gibbs reactor	Calculation mode: adiabatic
Turbine	Expander	Outlet pressure: 1 atm, efficiency: 95%

Table 5

Equipment used for modeling the closed loop plant

Equipment	Model	Operating condition
Air compressor	Compressor	Pressure ratio: 9.5, efficiency of 95%
Combustor	Mixer	Pressure calculation: maximum inlet
	Gibbs reactor	Calculation mode: adiabatic
Air compressor 2	Compressor	Outlet pressure: 20 atm, efficiency: 95%
Heating Heat exchanger	Heating heat exchanger	Heat transfer coefficient: 100 W/m^2K Heat transfer area: 1000 m^2
Turbine	Expander for generator	Outlet pressure: 1 atm, efficiency: 98%
Cooling Heat exchanger	Cooling heat exchanger	Heat transfer coefficient: 100 W/m^2K Heat transfer area: 1000 m^2

Various equipment is needed for the modeling of the process plants were identified and modeled using the relevant data provided in Table 4 and 5 for both the open and closed loop case. Although, equipment like combustors were modeled as a combination mixer and Gibb reactor since DWSim Gibb reactor does not allow one to charge in more than one inlet stream. Details of the equipment model across the plants are presented in Table 4 for the open loop and Table 5 for the closed loop.

2.2. Design of Experiment for the Optimization of the Power Generation

In the study, the experiment was designed with the use of Design Expert version 6.0.6 employing response surface methodology (central composite design) and was run 13 times, whose output was later employed in the optimization of the power generation process conditions. Open-loop process was use to understand the impact of compressor and turbine efficiency on power generation for open-loop (PG_O) and syngas temperature (T_{S4}), while closed-loop one was used to understand the impact of heat transfer coefficient and area on the power generation for closed-loop (PG_C).

Table 6

Design for compressor and turbine efficiency impact on PGo and T_{S4}

Response Variable	Variable Name	Units	Obs.	Study Type	Experiments	Initial Design
Y1	Power Gen.	kW	13	Response Surface	13	Central Composite
Y2	Syngas Temp.	K	13			
Factor Variable	**Variable Name**	**Units**	**Low Actual (L_A)**	**High Actual (H_A)**	**Low Coded (L_C)**	**High Coded (H_C)**
A (coded)	Comp. Eff. (actual)	%	39.75	79.25	-1	1
B (coded)	Turb. Eff (actual)	%	39.75	79.25	-1	1

Note: HPHT − high pressure high temperature stream; A and B − factor variables (in a normalized form with no unit); Y1 and Y2 − response variables; Obs. − number of observations; Comp. Eff. − compressor efficiency, %; Turb. Eff. − turbine efficiency, %.

For the determination of the coded values (otherwise known as the normalized form of the independent or factor variables assessed in the study) of the turbine and the compressor efficiencies for the different variations, equation 1 below is used.

$$y = \frac{(x-L_A)(H_C-L_C)}{(H_A-L_A)} + L_C, \quad (1)$$

where: x is value in actual form; y-value in coded form; L_A - low actual value; H_A - high actual value; L_C - low coded value, H_C- high coded value.

Table 7

Design summary with no blocks for impact of heat transfer coefficient and heat transfer area on HPHT gas stream temperature (T_{S5}) and power generated for closed-loop (PG_C)

Response Variable	Variable Name	Units	Obs.	Study Type	Experiments	Initial Design
Y1	HPHT Temp.	K	13	Response Surface	13	Central Composite
Y2	Power generated	kW	13			
Factor Variable	**Variable Name**	**Units**	**Low Actual (L_A)**	**High Actual (H_A)**	**Low Coded (L_C)**	**High Coded (H_C)**
A (coded)	Ht Trns. Coeff. (actual)	W/m^2K	28.87	120	-1	1
B (coded)	Ht Trns. Area (actual)	m^2	179.86	1000	-1	1

Note: HPHT − high pressure high temperature stream; A and B − factor variables (in a normalized form with no unit); Y1 and Y2 − response variables; Obs. − number of observations; Ht Trns. Coeff. − heat transfer coefficient, W/m2K; Ht Trns. Area - heat transfer area, m^2.

For the first case, the factors compressor and turbine efficiencies were varied in order to determine the optimal response variables (i.e., the power generation and syngas temperature) and the experiments were run 13 times. The variations of the factors were limited to a range between 39.75% (less efficient) and 79.25% (more efficient). This design summary is presented in Table 6.

For the second case, the HPHT temperature and power generated were the responses recorded from variation of the factors which are the heat transfer area and heat transfer coefficient. After 13 runs with the factors limited between a range of 28.87 W/m^{2}K (small) to 12087 W/m^{2}K (bigger) for heat transfer coefficient and 179.86 m^2 (small area) to 1000 m^2 (large area) for the heat transfer coefficient. The design summary is presented in Table 7.

3. Results

3.1. Process Flow Diagram for Modelling of the Gas-Turbine Power Plant

In this section, we presented the various process power plant that we explored in our study using both the process flow diagram (PFD) and block flow diagrams (BFD). The processes explored in the use of gas-turbine power plant include the open-loop and closed-loop process technologies.

3.1.1. Open Loop Process

Following the process flow diagram and block flow diagrams presented in Figures 2 and 3, we presented the block flow employed in the modeling of the open-loop gas-turbine power plant, which was successfully modeled in a DWSim package show in the process flow diagram, in Figures 2 and 3.

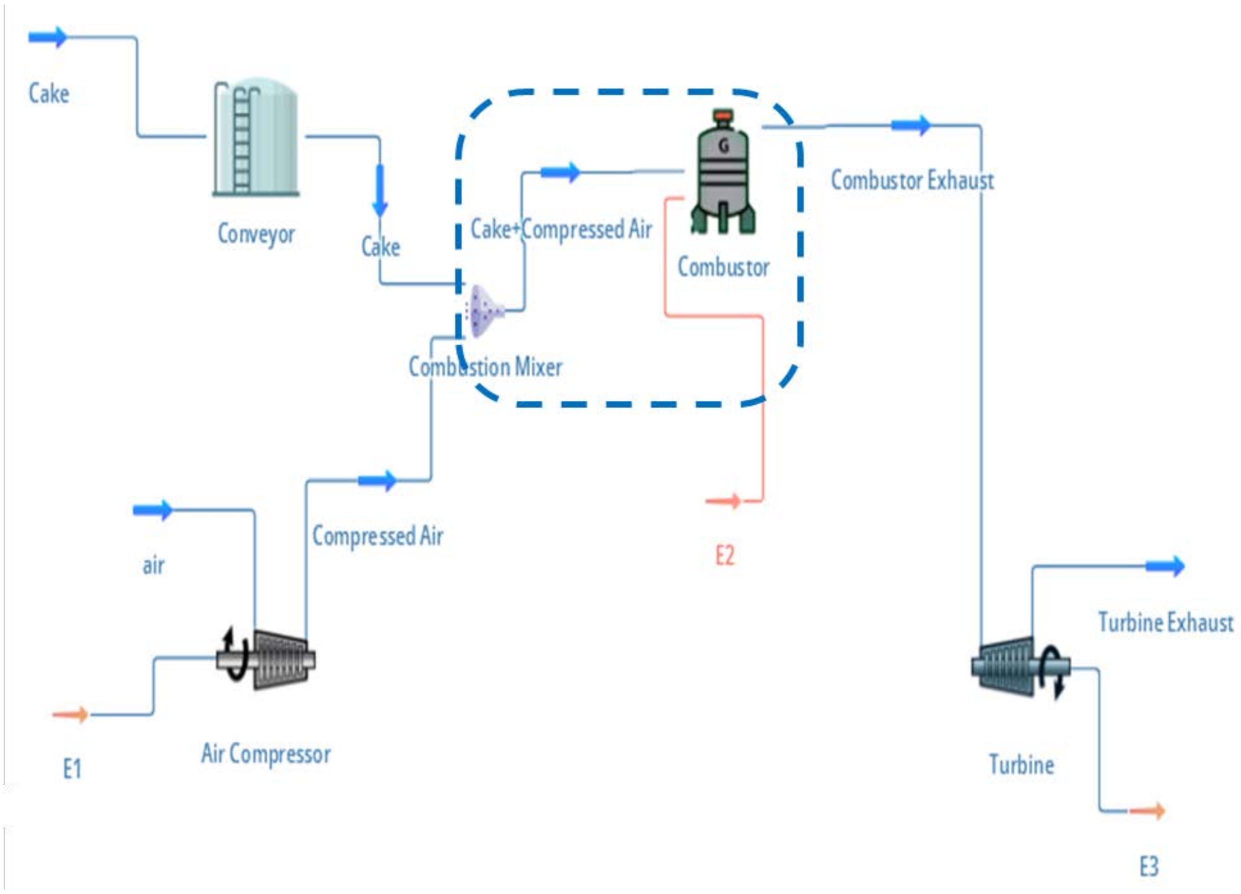


Figure 2. Biomass-fueled open-loop gas-turbine power plant (Process flow diagram).

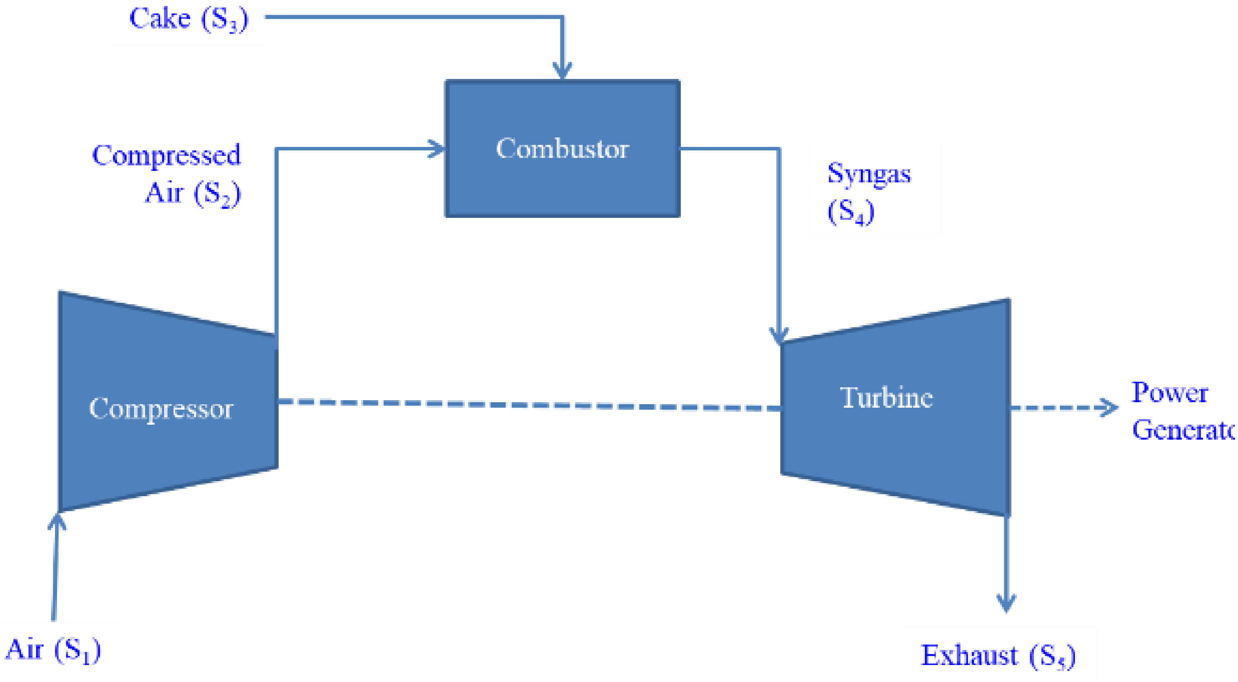


Figure 3. Biomass-fueled open-loop gas-turbine power plant (Block flow diagram).

The process entails series of process equipment like conveyor, compressor, turbine, and combustor (a reacting chamber) as shown in Figures 2 and 3. The power plant deployed the use of the Jatropha cake (that is, the residue of the Jatropha oil extraction process), where the conveyor was employed to transport and feed the combustor while the air is fed via the use of compressor.

After which, the cake is combusted in the presence of sufficient air to produce the high-pressure syngas as its exhaust, which is later used in driving the power plant turbine to generate the power or energy.

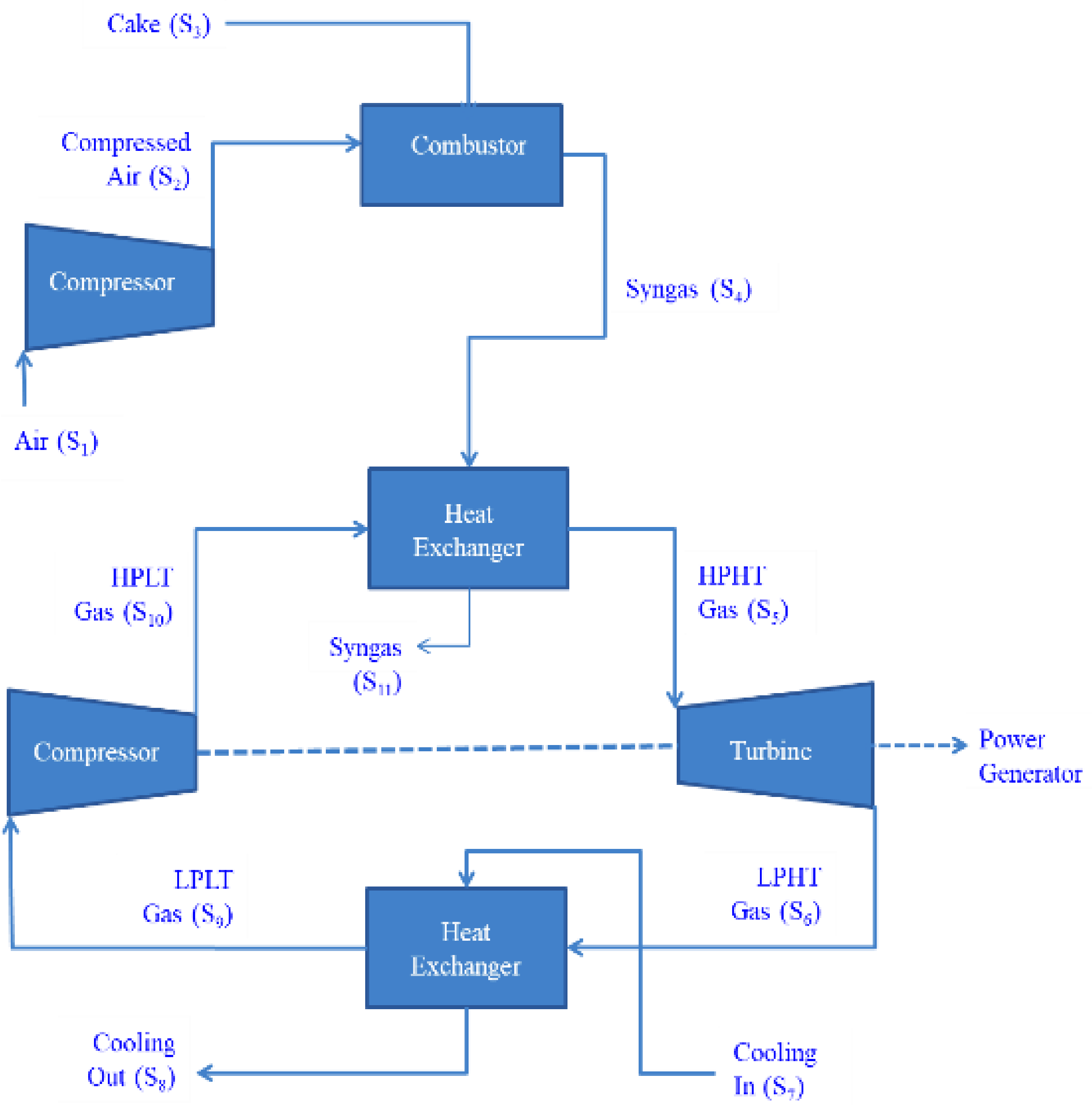
3.1.2. Closed-Loop Process

The process flow diagram and block flow diagram used in modeling the closed-loop gas turbine power plant in the DWSim package were shown in Figure 4. The process consisted of various pieces of equipment, including a conveyor, compressor, turbine, combustor (a reaction chamber), heat exchangers, and a working fluid (such as helium, nitrogen, or argon), as shown in Figure 4. Jatropha cake, a residue from the Jatropha oil extraction process, was used as the feed.

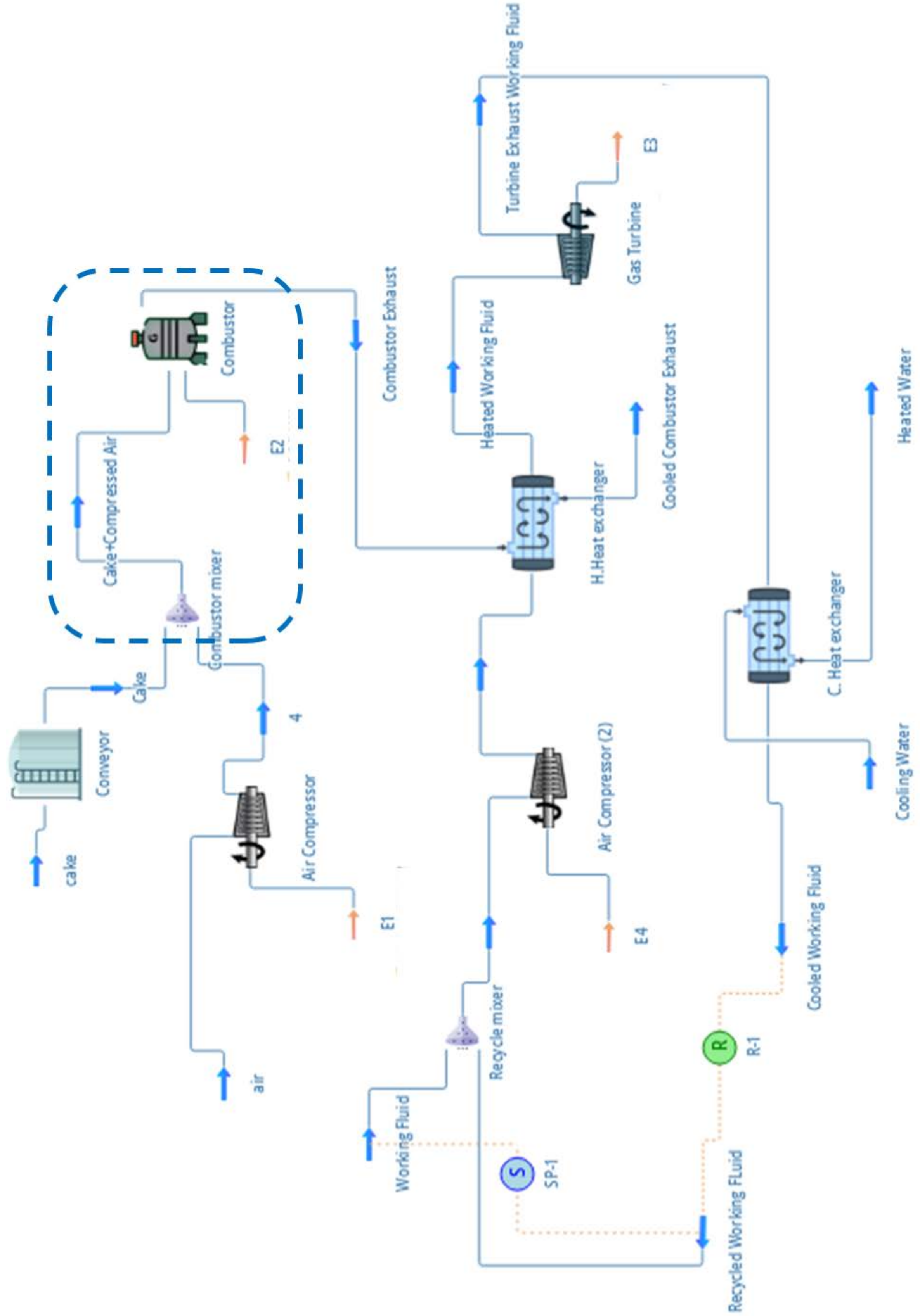
The conveyor transported the feed to the combustor, while air was supplied via the compressor. In the presence of sufficient air, the cake underwent combustion in the combustor, producing high-pressure syngas at a high temperature, which then became the combustor exhaust.

This exhaust was used to heat the working fluid (which was introduced into the system via the compressor) to an appropriate temperature using a heat exchanger.

After the heat is transferred from the combustor exhaust to the working fluid, the working fluid, which is at high pressure and temperature, is used to drive the power plant gas turbine. After power generation, the exhaust from the turbine, which contains the working fluid at lower pressure and temperature, is cooled in another heat exchanger using a cooling water stream and then recycled for reuse or re-circulation.


Cake (S_3)
Compressed Air (S_2)
Combustor
Compressor
Syngas (S_4)
Air (S_1)
Heat Exchanger
HPLT Gas (S_{10})
HPHT Gas (S_5)
Syngas (S_{11})
Compressor
Turbine
Power Generator
LPLT Gas (S_9)
LPHT Gas (S_6)
Heat Exchanger
Cooling Out (S_8)
Cooling In (S_7)

a)



b)

Figure 4. Biomass-fueled closed-loop gas-turbine power plant: a) block flow diagram and b) process flow diagram for the process plant.

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3.2. Impact of Compressor and Turbine Efficiency on Power Generation

3.2.1. Open Loop Gas-turbine Power Plant

a. Model screening analysis for the prediction of power generated

The results obtained from our analysis of the biomass-based gas-turbine power plant for the development of the PG_O prediction model are presented in Table 8. In the analysis, we evaluated the suitability of using linear, two-factor interaction (2FI), quadratic, and cubic models to predict power generation based on relevant independent variables (factors).

Table 8

Model summary statistics for the analysis of variance (ANOVA) and other statistical analysis parameters for the prediction of power generation for open loop (PG_O)

Source	SS	DF	MS	F Value	P-value	RSqr.	Adj. RSqr.	Pred. RSqr.
Linear	1.70E+10	2	8.52E+09	376.34	< 0.0001	0.9869	0.9843	0.9742
2FI	5.90E+06	1	5.90E+06	0.24	0.6353	0.9872	0.9830	0.9719
Quadratic	2.11E+08	2	1.05E+08	73.14	< 0.0001	0.9994	0.9990	0.9959
Cubic**	9.11E+06	2	4.55E+06	23.59	0.0028	0.9999	0.9999	0.9964
Residual	9.65E+05	5	1.93E+05					
Total	9.53E+10	13	7.33E+09					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; (**) – aliased model (that is, unsuitable model due to the failure of the model to distinguish effect of two or more variables in its model).

As shown in Table 8, the ANOVA analysis indicates that both the linear and quadratic models are suitable for predicting the amount of power generated, based on their P-values, which were found to be less than 0.05, in agreed with related report [29] that indicate that P-values less than 0.05 is insignificant. Additionally, these models exhibited higher values for their SS and MS compared to the cubic and 2FI models, which had higher P-values. Further analysis of the top-rated models (linear and quadratic) was conducted using R-squared values, as shown in Table 8. The results confirmed that both models are highly reliable, with R-squared values greater than 95%. However, the quadratic model was rated higher due to its superior P-value and R-squared value, which further validated its predictions in agreement with the interpretation presented in the literature [21,30].

b. Model analysis for the prediction of power generated for open-loop (PG_O)

The quadratic model developed for predicting PG_O is presented in the following equation (in coded form of the factors explored in the study):

$$PG_O = 80723.20 + 15793.88A + 43372.29B - 5428.24A^2 + 173.56B^2 - 1214.83AB, \text{ (kW)} \quad (2)$$

where: A is compressor efficiency (Comp. Eff. no unit) and B is turbine efficiency (Turb. Eff. non unit).

The analysis of the most suitable model (quadratic) shows that the constant term (also known as the average) is 80723 kW. Among the factors, B has the most significant effect on power generation, as indicated by its higher coefficient (43372.29). In contrast, A has a lesser effect, as shown by its lower coefficient (15793.88). In general, the interaction terms (A^2, B^2, and A*B) were found to have a smaller effect on power generation compared to the single-factor effects (A and B). This conclusion is based on the higher coefficients reported for the single-factor terms (A and B) compared to the interaction terms (A^2, B^2, and A*B).

Findings from this quadratic analysis further explain why the linear models demonstrated good prediction capabilities in Table 8 (as discussed in the previous section). These results confirm that compressor and turbine efficiencies have a predominantly linear relationship with power generation. However, the quadratic model reveals that the inclusion of non-linear terms, such as A^2 and B^2, significantly improves prediction accuracy, as evidenced by the results in Tables 8 and 9.

Table 9

ANOVA and other statistical analysis parameters for response surface quadratic model for the prediction of Power Generated for open-loop (PG_O)

Source	SS	DF	MS	F Value	Prob > F	Statistic Parameter	Value
Model	1.73E+10	5	3.45E+09	2399.28	< 0.0001	RSqr.	0.9994
A	2.00E+09	1	2.00E+09	1386.91	< 0.0001	Adj RSqr.	0.9990
B	1.51E+10	1	1.51E+10	10459.13	< 0.0001	Pred RSqr.	0.9959
A^2	2.05E+08	1	2.05E+08	142.46	< 0.0001		
B^2	2.10E+05	1	2.10E+05	0.15	0.7141		
AB	5.90E+06	1	5.90E+06	4.10	0.0825		
Residual	1.01E+07	7	1.44E+06				
Lack of Fit	1.01E+07	3	3.36E+06				
Pure Error	0	4	0				
Cor Total	1.73E+10	12					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; A – compressor efficiency; B – turbine efficiency.

Further analysis of the model in Table 9 indicates that the B^2 (quadratic factor) and interaction term (A*B) in the quadratic model have no significant impact on the amount of power generated by the power plant using Jatropha cake as feedstock due to its P-value that is higher than 0.05, which confirms it to be insignificant following the literature [31,32].

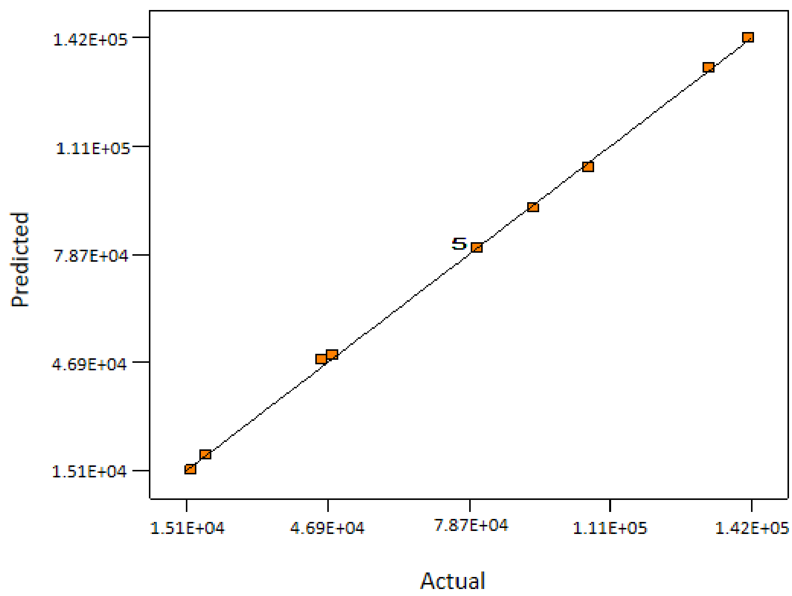

Figure 5. A plot of predicted vs. actual value of PG_O.

Conversely, other terms, including A, B, and the quadratic effect of A, were found to have a more significant influence on the power output of the evaluated process. Additionally, Figure 5 further emphasizes the accuracy of the quadratic model, demonstrating a strong alignment between the actual and predicted values.

3.2.2 Impact of Compressor and Turbine Efficiency on Syngas(S_4) Temperature

a. Screening analysis for the syngas (S4) temperature model

The results obtained from the analysis of the biomass-based gas-turbine power plant for the development of the syngas temperature model is presented in Table 10. In the analysis, the suitability of using various models (including linear, two-factor interaction (2FI), quadratic, and cubic models) for predicting the syngas temperature based on relevant independent variables was evaluated.

Table 10

Model summary statistics for the analysis of variance (ANOVA) and other statistical analysis parameters for the prediction of syngas (S_4) Temperature.

Source	SS	DF	MS	F Value	Prob>F	RSqr.	Adj. RSqr.	Pred. RSqr.
Linear	6.15E+04	2	3.07E+04	47.08	< 0.0001	0.904	0.8848	0.8118
2FI	0	1	0	0	1	0.9040	0.8720	0.7887
Quadratic	6.26E+03	2	3.13E+03	79.77	< 0.0001	0.9960	0.9931	0.9713
Cubic**	2.48E+02	2	1.24E+02	23.50	0.0029	0.9996	0.9991	0.9752
Residual	26.39	5	5.28					
Total	1.21E+08	13	9.30E+06					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; A – Compressor efficiency; B – Turbine efficiency; (**) - aliased model (that is, unsuitable model due to the failure of the model to distinguish effect of two or more variables in its model).

The results in Table 10, showing the ANOVA analysis, reveal that both the linear and quadratic models are suitable for predicting the syngas temperature. This conclusion is based on the low P-values (less than 0.05) and the higher SS and MS values compared to the other models (cubic and 2FI), which had higher P-values, in accordance with statistical interpretation reported in the literature [30]. Further analysis of the two best-rated models (linear and quadratic) was conducted using the R-squared values. As observed from Table 10, both models are highly reliable, with R-squared values greater than 95%. Although the quadratic model was rated higher due to its superior P-value and R-squared value, making it the most suitable model, which agrees with the literature report [30,33].

b. Model development and analysis for the prediction of syngas (S4) temperature (Ts_4)

The quadratic model developed for predicting the Ts_4 is presented in the following equation (both in coded and actual form of the factors explored in the study):

$$Ts_4 = 3030.29 - 87.67A + 2.500E\text{-}003B + 29.60A^2 - 0.91B^2 + 5.000E\text{-}003AB, \text{ (K)} \quad (3)$$

where: A is compressor efficiency (Comp. Eff no unit) and B is turbine efficiency (Turb. Eff no unit).

The analysis of the quadratic model shows that the constant term is 3030.29 K. The factors with the most significant effect on the Ts_4 are A with a coefficient of 87.67 and the interaction term A^2 with a coefficient of 29.60. These factors have higher coefficients compared to the other factors, which are B, and the interaction terms B^2 and A*B, with coefficients of 2.500E-003, 0.91, and 5.000E-003, respectively. The findings made also aligns with the trend of the P-values report for each factor in relation with the literature report [29,32], which states P-values greater than 0.05 confirm B, B^2, and A*B insignificant. The negative sign of the factor A coefficient implies that as the value of A increases, the response variable (Ts_4) decreases initially but the positive value of the coefficient of A^2 suggests that further increase in A will lead to an increase in $T_{s4.}$

Table 11

ANOVA and other statistical analysis parameters for response surface quadratic model for the prediction of syngas (S_4) Temperature (Ts_4).

Source	SS	DF	MS	F Value	Prob > F	Statistic Parameter	Value
Model	67749.3	5	13549.86	345.55	< 0.0001	RSqr.	0.9960
A	61493.59	1	61493.59	1568.23	< 0.0001	Adj RSqr.	0.9931
B	5.00E-05	1	5.00E-05	1.275E-06	0.9991	Pred RSqr.	0.9713
A2	6094.77	1	6094.77	155.43	< 0.0001		
B2	5.74	1	5.74	0.15	0.7134		
AB	1.00E-04	1	1.00E-04	2.550E-06	0.9988		
Residual	274.48	7	39.21				
Lack of Fit	274.48	3	91.49				
Pure Error	0	4	0				
Cor Total	68023.79	12					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; A – compressor efficiency; B – turbine efficiency.

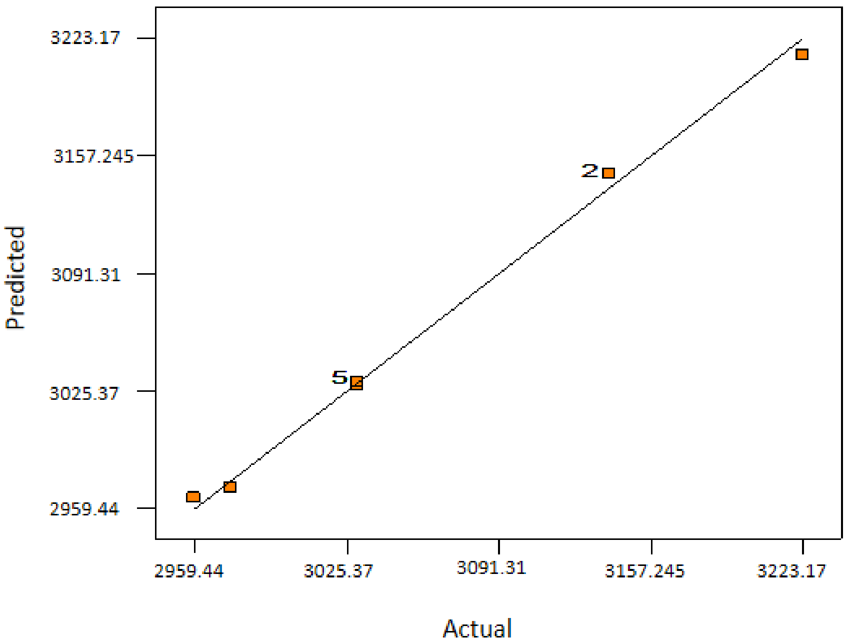

Figure 6. A plot of predicted vs. actual value of Syngas (S_4) Stream Temperature (T_{S4}).

Results of the quadratic model analysis confirm that compressor efficiency has a predominantly linear relationship with the Ts_4. From further analysis of the model in Table 11, it is observed that factors associated with A have the most significant effect on Ts_4, while factors associated with B have very little effect on the Ts_4. This is further justified by the position of the stream (S4), as the stream is positioned before the turbine therefore the turbine parameters have no effect on Ts_4. Additionally, the accuracy of the quadratic model is further emphasized in Figure 6, which depicts a strong alignment between the actual and predicted values.

3.2.3. Optimization Criteria, Solution, and Validation

In the search for better conditions to produce improved power generation, we used the criteria stated in Table 12 for optimizing the power generation capacity, while constraining the compressor and turbine efficiencies to a specified range presented in Table 12, and keeping the Jatropha cake feed quantity constant.

Table 12

Criteria for Optimizations

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Comp. Eff.	In range	20	98	1	1	3
Turb. Eff	In range	20	98	1	1	3
Power Gen.	Maximize	16283	200000	1	1	3
S_4 Temp.	In range	2959.44	3223.17	1	1	3

Note: S4 Temp. – stream S4 temperature; Comp. Eff. – compressor efficiency Turb. Eff. – turbine efficiency; Power Gen. – power generated.

Table 13

Results for Optimization and Validation

Solution	Comp. Eff. (%)	Turb. Eff (%)	Power Gen. (kW)	S_4Temp. (T_{S4}) (K)	Desirability
Optimized	83.92	98	174235	2963.70	0.86
Validated	83.92	98	174518	2965.77	-

Note: S4 Temp. – stream S4 temperature; Comp. Eff. – compressor efficiency Turb. Eff. – turbine efficiency; Power Gen. – power generated.

Using a numerical approach to optimize the power generation with the constraints stated in Table 12, the optimum Ts_4, compressor efficiency (Comp. Eff.), and turbine efficiency (Turb. Eff.) in the Jatropha cake-to-power process yielded an optimum power output of 174,235 kW and an Ts_4 of 2963.70 K, as shown in Table 13, with a desirability of 86%. The comparison of the optimized solution and the validation results for the optimum power generated shows good agreement with an insignificant difference. The findings suggest that running the power plant turbine and compressor below the confirm optimum efficiency could results to a much more lower power output in the said plant.

3.3. Impact of Heat Transfer Coefficient and Heat Transfer Area on Closed-Loop Gas-turbine Power Plant

3.3.1. Impact of Heat Transfer Coefficient and Heat Transfer Area on Heat Exchanger Heated Stream Temperature

a. Screening analysis for the prediction model for HPHT gas (S5) stream temperature (*Ts_5*)

The results obtained from our analysis of the biomass-based closed-loop gas-turbine power plant for the development of the Ts_5 model are presented in Table 14. The evaluation of the suitability of using linear, quadratic, two-factor interaction (2FI), and cubic models for predicting the Ts_5 was carried out in the analysis.

Table 14

Model summary statistics for the analysis of variance (ANOVA) and other statistical analysis parameters (Note: **aliased model)

Source	SS	DF	MS	F Value	P-value	RSqr	Adj. RSqr	Pred. RSqr
Linear	1.55E+05	2	77251.37	69.85	< 0.0001	0.9332	0.9198	0.8647
2FI	6846.57	1	6846.57	14.63	0.0041	0.9746	0.9661	0.9332
Quadratic	3222.18	2	1611.09	11.38	0.0063	0.9940	0.9897	0.9574
Cubic**	990.94	2	495.47	25650.74	< 0.0001	1	1	1
Residual	0.097	5	0.019					
Total	1.21E+07	13	9.29E+05					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; (**) – aliased model (that is, unsuitable model due to the failure of the model to distinguish effect of two or more variables in its model).

As presented in Table 14, the ANOVA analysis indicates the suitability of both the linear and quadratic models for predicting the Ts_5. This suitability is based on the P-values, which were found to be less than 0.05, in agreement with the reports [29,31] in the literature. Furthermore, the values of the SS and MS were higher for these models compared to the other models (cubic and 2FI).

Using the R-squared values of the identified best-rated models (linear and quadratic), the reliability was confirmed, with both models exhibiting an R-squared value greater than 90%. Although both models exhibited R-squared values above 90%, the quadratic model had the higher value, which rated it as the most suitable model for prediction.

b. Model analysis for the prediction of HPHT gas (S5) stream temperature (Ts_5)

The quadratic model developed for predicting the Ts_5 is presented in the following equation (in coded form of the factors explored in the study):

$$Ts_5 = 976.91 + 90.38A + 105.56B - 13.92A^2 - 18.09B^2 + 41.37AB, \text{(K)} \quad (4)$$

where: A is the heat transfer coefficient (Ht. Trns. Coeff. no unit) and B is the heat transfer area (Ht. Trns. Area no unit).

Analysis of the quadratic model shows that the constant term (also known as the average) is 976.91 K. It is evident from the coefficients of the various factors that B, with a higher coefficient of 105.56, has the most significant effect on the Ts_5, in contrast to the A with a coefficient of 90.38.

In comparison to the single factors A and B, the interaction terms A^2, B^2, and A*B, with coefficients of 13.92, 18.09, and 41.37 respectively, have a lesser effect on the Ts_5. The findings from this quadratic model indicate the linear relationship between the heat transfer coefficient (A) and heat transfer area (B) with the Ts_5. Moreover, the model also shows that the inclusion of non-linear terms, such as A^2 and B^2, significantly improves the prediction accuracy, as seen in Tables 14 and 15.

Upon further analysis of the quadratic model in Table 15, it is evident that the quadratic factors AA and BB and the interaction term A*B have no significant impact on the Ts_5. the other terms which include A and B showed greater significance on the Ts_5.

Table 15

ANOVA and other statistical analysis parameters for response surface quadratic model for the prediction of HPHT Gas (S_5) Stream Temperature.

Source	SS	DF	MS	F Value	P-value	Statistic Parameter	Results
Model	1.65E+05	5	32914.3	232.48	< 0.0001	RSqr.	0.994
A	65354.81	1	65354.81	461.62	< 0.0001	Adj RSqr.	0.9897
B	89147.93	1	89147.93	629.68	< 0.0001	Pred RSqr.	0.9574
A^2	1347.35	1	1347.35	9.52	0.0177		
B^2	2276.93	1	2276.93	16.08	0.0051		
AB	6846.57	1	6846.57	48.36	0.0002		
Residual	991.04	7	141.58				
Lack of Fit	991.04	3	330.35				
Pure Error	0	4	0				
Cor Total	1.66E+05	12					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; A – Heat transfer coefficient (Ht. Trns. Coeff.), B - Heat transfer area (Ht. Trns. Area).

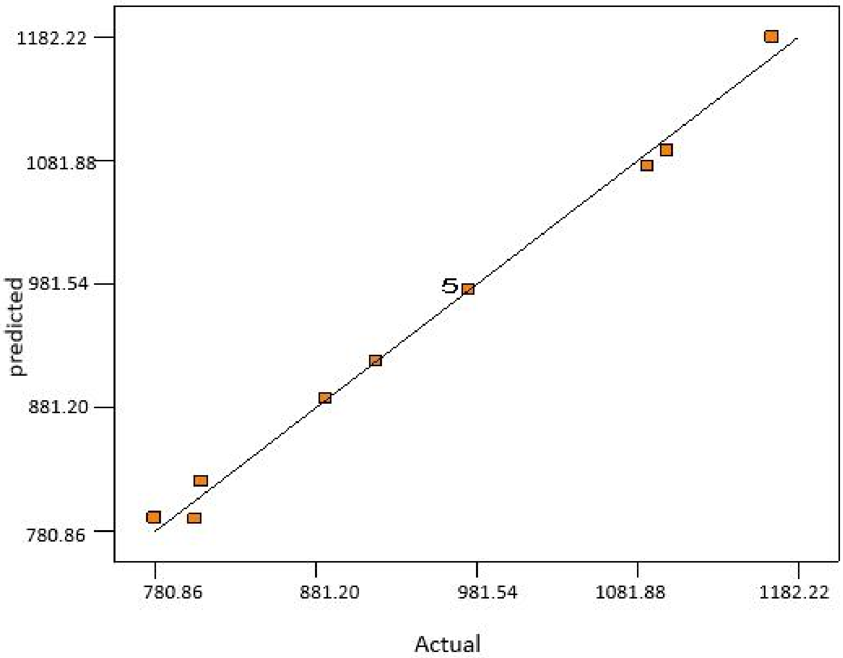

Figure 7. A plot of predicted vs. actual value of HPHT Gas (S_5) Stream Temperature.

The accuracy of the quadratic model is further emphasized in Figure 7 which shows the alignment between the actual and predicted values.

3.4. Impact of Heat Transfer Coefficient and Heat Transfer Area on Power Generation

3.4.1. Screening analysis for the prediction model for the power generated for closed-loop (PG_C)

The results obtained from the analysis of the biomass-based gas-turbine power plant for the development of the power generation prediction model is presented in Table 16 Evaluation of the suitability of using linear, two-factor interaction (2FI), quadratic, and cubic models for predicting power generation using relevant independent variables (factors) was carried out in this analysis.

Table 16

Model summary statistics for the analysis of variance (ANOVA) and other statistical analysis parameters for the prediction of power generated for closed-loop (PGc)

Source	SS	DF	MS	F Value	P-value	RSqr	Adj. RSqr	Pred. RSqr
Linear	9.92E+09	2	4.96E+09	69.86	< 0.0001	0.9332	0.9198	0.864
2FI	4.54E+08	1	4.54E+08	15.99	0.0031	0.9759	0.9679	0.9365
Quadratic	1.95E+08	2	9.74E+07	11.19	0.0066	0.9943	0.9902	0.9592
Cubic**	6.09E+07	2	3.04E+07	4518.85	< 0.0001	1	1	0.9998
Residual	33686.48	5	6737.3					
Total	1.44E+10	13	1.11E+09					

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; (**) – aliased model (that is, unsuitable model due to the failure of the model to distinguish effect of two or more variables in its model).

Table 16 shows the ANOVA analysis, which indicates that both the linear and quadratic models, with P-values less than 0.05, are suitable for predicting the amount of power generated. This was due to its P-value that is higher than 0.05, which confirms it to be insignificant following the literature [31,32]. Upon further analysis, their SS and MS values also exhibited higher values. The best-rated models were chosen based on a comparison of their various R-squared values. From this comparison, it is evident that the quadratic model exhibited the higher R-squared value among the best-rated models, in accordance with the literature [33,34] interpretation for higher R-squared value. For this reason, the quadratic model was chosen.

3.4.2. Model analysis for the prediction of power generated for closed-loop (PG_C)

The quadratic model developed for the prediction of PG_C is presented in Equation (in coded form of the factors explored in the study):

$$PG_C = 21940.90 + 22915.61*A + 26734.57*B - 3427.62*A^2 - 4444.07*B^2 + 10656.33*A*B, \text{ (kW)} \quad (5)$$

where: A is Heat transfer coefficient (Ht. Trns. Coeff. no unit) and B is heat transfer area (Ht. Trns. Area no unit).

The analysis of the quadratic model shows that the constant term is 21940.90 kW and although both factors A and B have high and close values, the factor with the greater effect on the power generated is the B due to its higher coefficient (26734.57). By comparing the coefficients, the interaction terms A^2, B^2 and A*B were found to have less effect on the power generated compared to the single-factors A and B.

Table 17

ANOVA and other statistical analysis parameters for response surface quadratic model for the prediction of power generated for closed-loop (PG_C)

Source	Sum of Squares	DF	Mean Square	F Value	P-value	Statistic Parameter	Value
Model	1.06E+10	5	2.11E+09	242.85	< 0.0001	RSqr	0.9943
A	4.20E+09	1	4.20E+09	482.69	< 0.0001	Adj RSqr	0.9902
B	5.72E+09	1	5.72E+09	656.98	< 0.0001	Pred RSqr	0.9592
A^2	8.17E+07	1	8.17E+07	9.39	0.0182		
B^2	1.37E+08	1	1.37E+08	15.79	0.0054		
AB	4.54E+08	1	4.54E+08	52.19	0.0002		
Residual	6.09E+07	7	8.70E+06				

Continuation Table 17

Lack of Fit	6.09E+07	3	2.03E+07
Pure Error	0	4	0
Cor Total	1.06E+10	12	

Note: SS – sum of square; DF – degree of freedom; MS – mean square; F Value – F test result; P-value – significance test; RSqr. – Rsquare value; Adj. RSqr. – adjusted Rsquare value; Pred. RSqr. – predicted Rsquare value; A – heat transfer coefficient (Ht. Trns. Coeff.); B - heat transfer area (Ht. Trns. Area).

Further analysis from Table 17 reveals that all the factors have a significant effect on the amount of power generated from the plant using Jatropha cake as feedstock. Further emphasis on the accuracy of the model is demonstrated in Figure 8, where a strong alignment between actual and predicted value is observed.

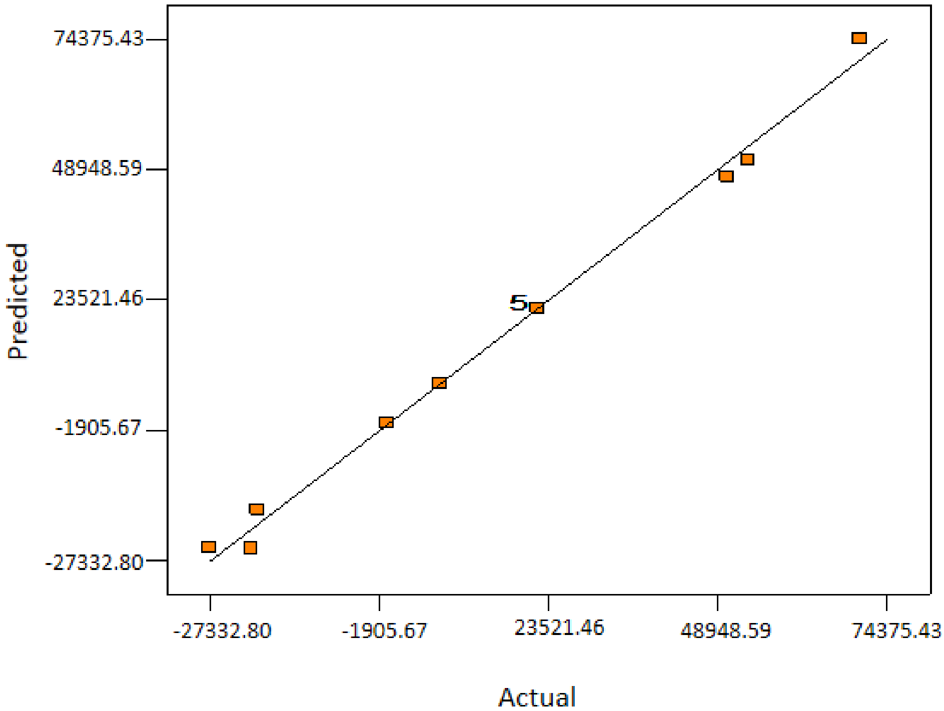

Figure 8. A plot of predicted vs. actual value of Power Generated.

3.4.3. Optimization Criteria, Solution, and Validation

The criteria employed for the optimization of power generation capacity are presented in Table 18. While keeping the Jatropha cake feed quantity constant, the heat transfer coefficient and heat transfer area were constrained to a specified range presented in the Table 18.

Table 18

Criteria for Optimizations

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Ht Trns. Coeff.	is in range	28.87	120	1	1	3
Ht Trns. Area	is in range	179.86	1000	1	1	3
Outlet Temp.	is in range	780.857	1500	1	1	3
Power generated	maximize	-27332.8	200000	1	1	3

Note: Ht Trns. Coeff. – heat transfer coefficient, W/m^2K; Ht Trns. Area - heat transfer area, m^2; Outlet Temp. – heating heat exchanger outlet temperature, K.

Table 19

Results for Optimization and Validation

Solution	Ht Trns. Coeff. (W/m^2K)	Ht Trns. Area (m^2)	Outlet Temp. (K)	Power generated (kW)	Desirability
Optimized	120	1000	1182.22	74375.7	0.447
Validated	120	1000	1166.08	70336.5	-

Note: Ht Trns. Coeff. – heat transfer coefficient; Ht Trns. Area – heat transfer area; Outlet Temp. – heating heat exchanger outlet temperature from raising the gas from a lower temperature (LT) to higher temperature (HT).

A numerical approach was employed in the optimization of the power generation using the constraints stated in Table 18. The optimum conditions were found to yield an outlet temperature of 1182.22 K and power generation of 74375.7 kW, respectively, with a desirability of 45%. The optimized and validated solution results show good agreement, with an insignificant difference in both outlet temperature (1182.22 and 1166.08) and power generated (74375.7 and 70336.5 kW). The findings made from the study suggest that the heat exchanger use in the power plant would be produced higher power out if sufficient transfer area of less than 1000 m^2 is made available and material with minimum heat transfer coefficient of 120 kW/m^2K for the heat transfer process.

5. Conclusions and Recommendations

In this study, a central composite design (CCD) approach was utilized to evaluate the effects of compressor efficiency, turbine efficiency, heat transfer coefficients, and heat transfer area (in a heat exchanger) on power generation in a prospective gas-turbine bio-power plant. The process was successfully modeled using the DWSim simulation package to simulate power generation from Jatropha cake. The study examined the effects of compressor and turbine efficiency using an open-loop gas-turbine power plant configuration, while the effects of heat transfer coefficient and area were analyzed using a closed-loop gas-turbine power plant configuration to identify optimal conditions.

The findings indicate that using a compressor with 83.92% efficiency and a turbine with 98.00% efficiency in an open-loop power plant would yield a maximum power output of 174235.0 kW from Jatropha cake. Additionally, the assessment of heat transfer area and coefficient in a closed-loop configuration revealed that values of 1000 m^2 and 120 W/m^2K, respectively, represent the optimal conditions for maximizing power generation to 74375.70 kW from Jatropha cake. These results were obtained through optimization studies carried out using the CCD design approach.

In a nutshell, the study therefore demonstrates that employing a compressor with a minimum efficiency of 83.92% and a turbine with a minimum efficiency of 98% in a gas-turbine power plant (open or closed-loop) would yield a promising power output using Jatropha cake. Furthermore, in a closed-loop system, where a heat exchanger (HX) is required, using an HX with a heat transfer coefficient of 120 W/m^2K and a heat transfer area of 1000 m^2 would result in significantly higher power generation. The deployment of these optimal conditions would substantially enhance power generation yield.

Further work could explore a modified form of the closed-loop gas-turbine power plant, which would introduce an additional turbine between the combustor and heat exchanger of the looped section of the power plant to determine whether this configuration could lead to an even higher power generation capacity.

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