Application of model and algorithms in improving methane yield in an industrial biogas plant

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Abstract. With the ever-growing application of data science and machine learning in the fourth industrial revolution era, many challenges faced within the energy sector in past decades have now been receiving timely interventions through the proper application of programming and machine learning tools coupled with the implementation and utilization of modern technology. In recent years, balancing in real-time the demand and supply of energy generated from renewable sources such as wind and solar has gained much improvement because of its ability to forecast the quantity of energy that could be produced from the renewable sources using historical data. Likewise, the application of model and algorithms has also helped to predict accurately, the amount of energy that could be produced from a batch of anaerobic digestion process to produce biogas or biomethane of acceptable quality. In this research work, a set of data was collected from an industrial biogas plant and based on the variables from the data set, Design Expert Software version 11 was used to develop mathematical models and algorithms to optimize the production process of the plant based on the feedstock fed into the digesters. The result of the optimization proves that the biogas currently produced from the post-digester tank with methane (CH_4) content of about 68.8% can be upgraded to biomethane with methane content of 78.22% without any adjustment to the digesters or production process.

Keywords: Algorithms, anaerobic digestion, biogas, biomethane, data science, model, optimization.

1 Introduction

Over many centuries, the cornerstone of the development of infrastructures globally and the provision of basic services had been energy derived from fossil fuel sources [1]. However, these had also contributed and impacted the environment in a negative way because of the release of harmful gases otherwise known as greenhouse gases and other toxic substances into the atmosphere. These toxic substances and greenhouse gases emanate mostly from the burning of coal, natural gas and oil for electricity and transportation which are the major contributors to global warming and climate change. Due to the combustion and utilization of fossil fuel over many decades, there has been a drastic increase in the atmospheric carbon dioxide (CO_2) emissions which is one of the main causes of global warming and climate change [2], [3].

The estimated increase in the amount of CO_2 according [4] is about 90% with the largest contributor being the industrial sector followed by the agricultural sector globally. To reduce emissions of heat-trapping greenhouse gases released into the atmosphere from fossil fuel

sources and prevent further the severity of global warming, there is a need to urgently explore alternative energy sources which are clean, eco-friendly, reliable, and sustainable. The generation of energy from renewable sources such as biomass, solar, wind and hydro are gradually gaining momentum due to advancements in Renewable Energy technologies and researchers' efforts which are constantly seeking ways to improve the sector with the aim of making energy derived from renewable energy readily available and affordable.
Biomass which has been reported to be the fourth largest energy resource in the world [5] has a huge potential to meet-up to a large extent the ever-growing demand for energy. However, just like any other renewable source of energy, the production of biofuel from biomass has been faced with numerous challenges ranging from complexities of biomass, logistics and technical challenges associated with processes such as pre-treatment, hydrolysis, microbial fermentation and fuel separation [6]. Despite these numerous and multi-faceted challenges, biofuel production is beginning to strive, and it is projected that the sector will continue to experience advancement until it becomes a leading source of transportation fuel in the future as shown in Figure 1.

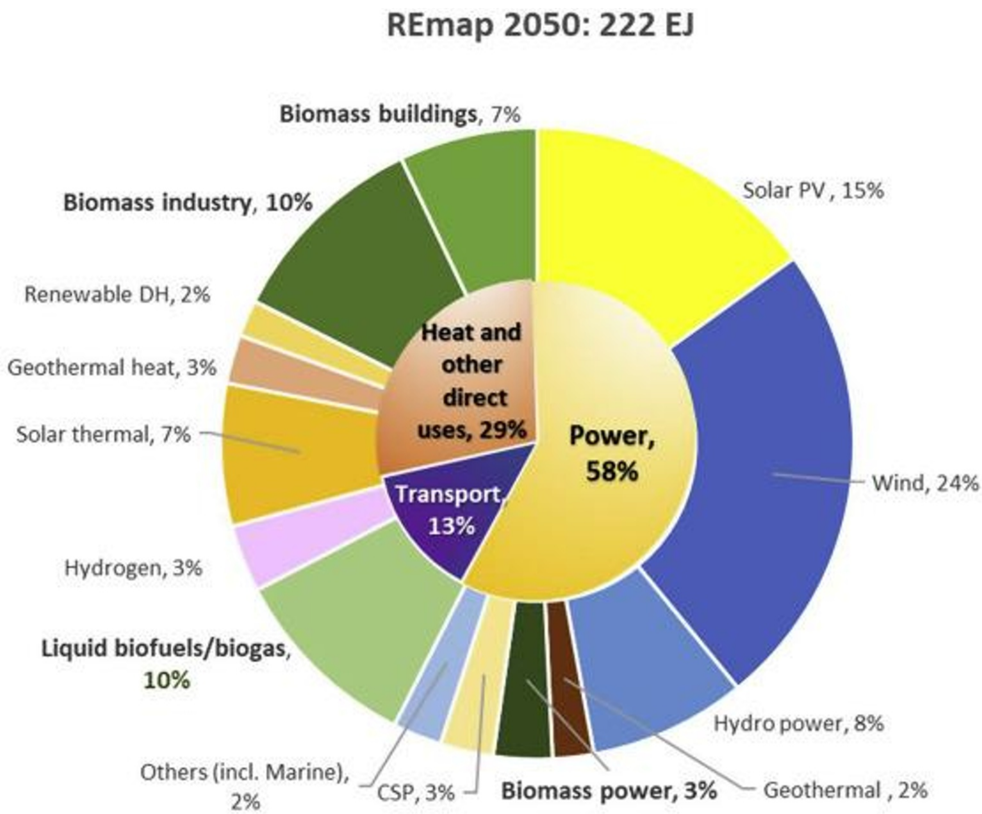

Fig. 1. Renewables utilization pathway projections, Remap 2050. Source: [7]

There are several alternatives to the consumption of petroleum-based fuel such as diesel and petrol which are major contributors to the emission of Carbon dioxide (CO_2) in the atmosphere including hydrogen, electricity, natural gas and biofuel which comprises of biogas, biodiesel, propane and ethanol. However, for the world to experience a successful transformation from the consumption of fossil fuel to biofuels produced from biobased materials which is technically deemed possible, there is a need for an integrated policy design in order to identify cost-effective "win-win" solutions that can deliver on multiple objectives simultaneously [8], [9]. Currently, there is still a wide gap between the transition due to many factors such as social-political, technology, costs and many others. It can be noted however that with consistent and dedicated effort towards the actualization of the sustainable development goals world leaders can make it a reality. The majority of biofuels currently consumed globally is attributed to the extraction of sugar from agricultural feedstock or the conversion of starch into sugars mainly from edible grains [6]. The utilization of biofuels produced from renewable sources in place of petroleum-based fuel in the transportation sector has its unique benefits namely better fuel economy, local production and distribution, less emission of greenhouse gases, reduction in foreign oil dependency, environmental friendliness and many more.

Different types of biofuels can be produced from various sources and extensive research has been done to substantiate the research findings that biogas can also be produced from various sources using different processes such as production from wastewater sludge [10]–[12], paper sludge [13], [14]; Co-digestion of animal dung with food waste and crop residue [15]–[17], municipal solid wastes [18]–[20] amongst others. The process of producing biogas, a type of biofuel from an Anaerobic Digestion (AD) process is a complex one which involves a multi-step anaerobic digestion or degradation of organic matter by bacteria and enzymes in the absence of oxygen [21].

In an AD process, different bacteria are involved in the breaking down of the organic matter often considered as feedstock at different stages or processes however, the most notable bacteria are the methane-producing bacteria otherwise known as methanogens. For AD to be maximized, the four (stages) of the degradation such as Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis which are dependent on each other must be operating at optimal efficiency. Biogas production from an AD process has been extensively investigated and documented in numerous research articles [22]–[26]. However, the current research work aims to shed light on the use of soft computing tools such as MATLAB to enhance the production of biogas from an industrial biogas plant using municipal solid waste and various types of feedstock blend in an Anaerobic Digestion plant.

2 Research methodology

For the modelling and optimization of the biogas production process, series of data was collected over a six-month period from an industrial biogas plant in South Africa. The data set was cleaned up to fix and eliminate errors that could arise as a result of incomplete, inconsistent and duplicated data supplied from the biogas plant. For the modelling, six (6) variables were considered namely: temperature, pH, total solid, volatile solid, moisture and FOS/TAC. These independent variables were categorized as A, B, C, D, E, F respectively however, for further model reduction they were represented by X_1, X_2, X_3, X_4, X_5 and X_6 accordingly while the expected response which is the biomethane yield was represented by variable "y". With "No transformation model" influencing the raw data and low R2 value, the statistical tool used was still able to choose and recommend the best model for the relationship between the predictors and the response.

For the optimization of the process, the effect of temperature and other processing parameters was considered, and 3D-plots were obtained as presented in the results and discussion section of this article. The optimum temperature at every phase of the AD process is a major determinant of biogas yield as a result it was considered as a constant while other processing parameters such as: pH, Total Solid, Volatile Solid, Moisture and FOS/TAC were considered a variable as it relates to methane yield. The reason for this is because different bacteria exhibit diverse traits at an ideal temperature within the three temperature phases which are psychrophilic, mesophilic and thermophilic phases [27] and an increase in temperature facilitates faster reactions thereby leading to a faster biogas yield. However, there are other

factors such as volatile fatty acids, digesters' working pressure, retention time and composition of the sublayers that play vital roles in the production of biogas through AD [28].
To increase the methane yield of the industrial biogas plant successful, there is a need to optimize the factors of production otherwise referred to as production parameters based on the data set supplied by the biogas company. Optimization, often referred to as quality improvement, is one of the most powerful tools in process integration. It involves the selection of "best" solution from most feasible results within a given number of situations or candidate solutions and the degree of goodness of the solution is quantified using an objective function which is to be minimized or maximized [29], [30]. Broadly, optimization techniques can be classified into two types namely single variable optimization and multi-variable optimization techniques [31]. For this research the multi-variable optimization technique was adopted due to the number of the process parameters which is six (6) and the expected response which is biomethane. For the effectiveness of the optimization process, a quadratic design model was used.

3 Results and discussion

The summary of the model functions and response is presented in Table 1. To a large extent, the quality and quantity of biogas produced from an anaerobic digestion is dependent on process parameters, the parallel and cross-linked reactions of the bacteria involved in the four stages of the AD processes.

Table 1. Sequential model of squares.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	3.404E+05	1	3.404E+05			
Linear vs Mean	175.34	6	29.22	1.59	0.	
2FI vs Linear	662.28	15	44.15	3.42	0.0002	Suggested
Quadratic vs 2FI	34.08	4	8.52	0.6467	0.6312	Aliased
Residual	882.69	67	13.17			
Total	3.422E+05	93	3679.30			

Furthermore, based on the selected model a statistical analysis was conducted on the 2FI model using Analysis of Variance (ANOVA) to analyse various factors that could have affected the given data set. The summary of the statistical analysis is presented in Table 2.

Table 2. ANOVA table for independent variables.

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	837.62	21	39.89	3.09	0.0002	significant
A-Temperature	15.09	1	15.09	1.17	0.2833	
B-pH	43.29	1	43.29	3.35	0.0713	
C-Total Solid	143.39	1	143.39	11.11	0.0014	
D-Volatile Solid	2.83	1	2.83	0.2191	0.6412	
E-% Moisture	105.69	1	105.69	8.19	0.0055	
F-FOS/TAC	45.04	1	45.04	3.49	0.0659	
AB	4.26	1	4.26	0.3301	0.5674	
AC	98.73	1	98.73	7.65	0.0072	
AD	130.73	1	130.73	10.12	0.0022	
AE	78.8	1	78.8	6.1	0.0159	
AF	13.54	1	13.54	1.05	0.3093	
BC	170.26	1	170.26	13.19	0.0005	
BD	7.57	1	7.57	0.5859	0.4465	
BE	135.92	1	135.92	10.53	0.0018	
BF	43.9	1	43.9	3.4	0.0694	
CD	7.79	1	7.79	0.6033	0.4399	
CE	147.37	1	147.37	11.41	0.0012	
CF	136.07	1	136.07	10.54	0.0018	
DE	111.92	1	111.92	8.67	0.0044	
DF	4.02	1	4.02	0.3112	0.5787	
EF	104.32	1	104.32	8.08	0.0058	
Residual	916.77	71	12.91			
Cor Total	1754.38	92				

To express the relationship between the response and the independent variables effectively, a mathematical model was developed using ANOVA. The mathematical model generated based on the coded factors is presented in Equation 1.

$$-3.532E+05 + 1.464E+05C + 1.478E+05E + 2371.05AC + 479.18AD + 1674.80AE + 11706.51BC + 5736.00BE - 376.46CE + 1.357E+05CF - 189.74DE + 1.430E+05EF \quad (1)$$

From the statistical analysis, it is observed that there are insignificant models based on Model F- values and Model P- values which are above 100 and 0.100 respectively. This necessitated a model reduction to improve the model and the final equation of the reduced model is presented in equation 2.0 with "y' being the response (methane yield).

$$y = -3.532E+05 + 1.464E+05x_3 + 1.478E+05x_5 + 2371.05\,x_1x_3 + 479.18x_1x_4 + 1674.80x_1x_5 + 11706.51x_2x_3 + 5736.00x_2x_5 - 376.46x_3x_5 + 1.357E+05x_3x_6 - 189.74x_4x_5 + 1.430E+05x_5x_6 \quad (2)$$

The result presented in the 3D plots considers optimal temperature at the post digester tank of the biogas plant while other processing parameters within the tank are considered variables as they relate to the methane produced. The interactions of the process parameters considered as they influence the methane yield are presented in Figure 2a-e. With (Figure 2a) showing the influence of pH and temperature, (Figure 2b) showing effects of total solid and temperature, (Figure 2c) presenting the relationship between volatile solid and temperature as it affects methane yield, (Figure 2d) illustrating the interactions between moisture and temperature and Figure (2e) showing the impact of FOS/TAC and temperature as it affects methane yield respectively.

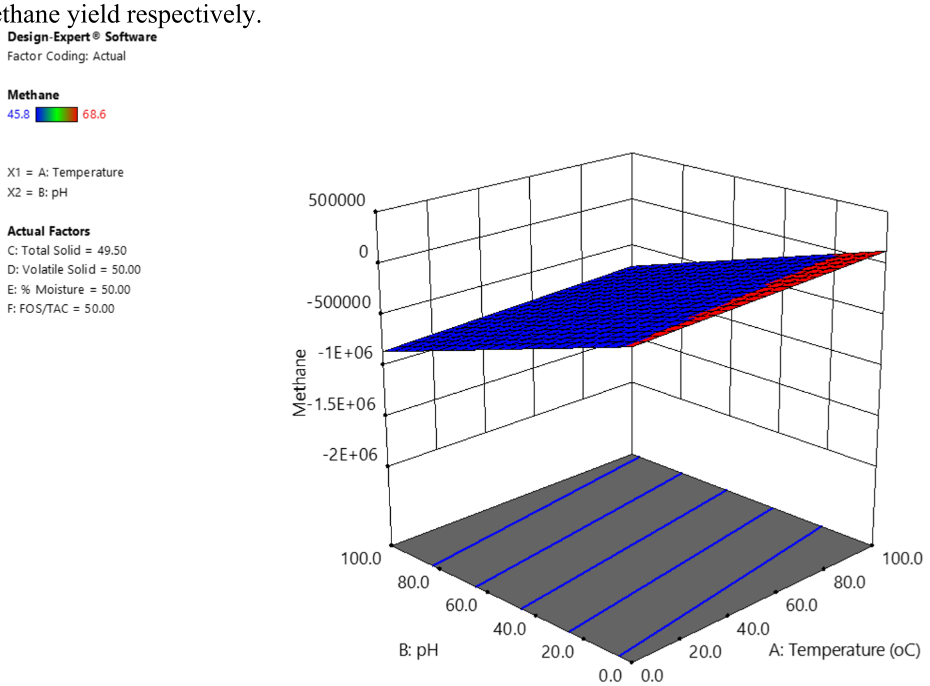

Fig. 2a. Interactive effect of pH and temperature on methane yield

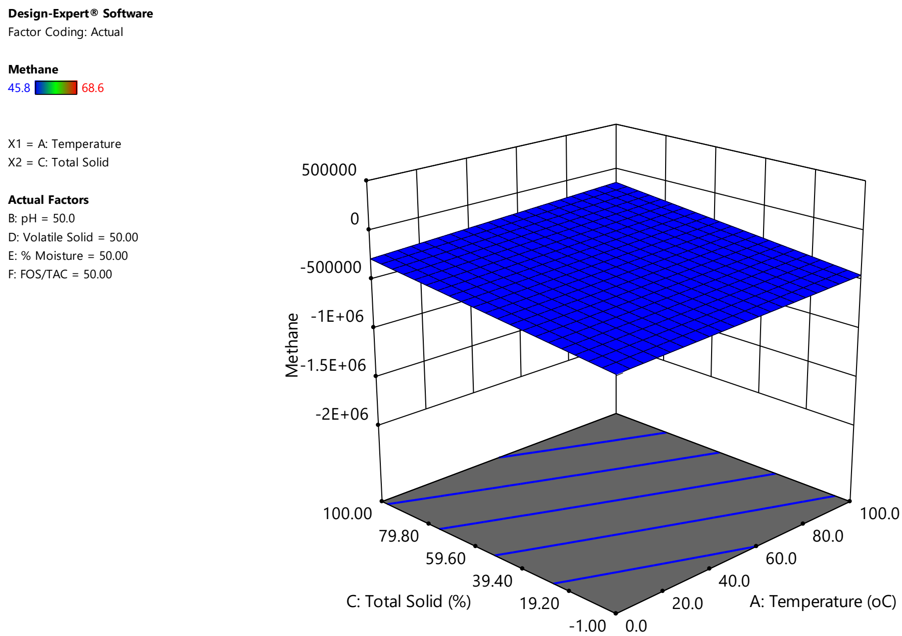

Fig. 2b. Interactive effect of total solid and temperature on methane yield

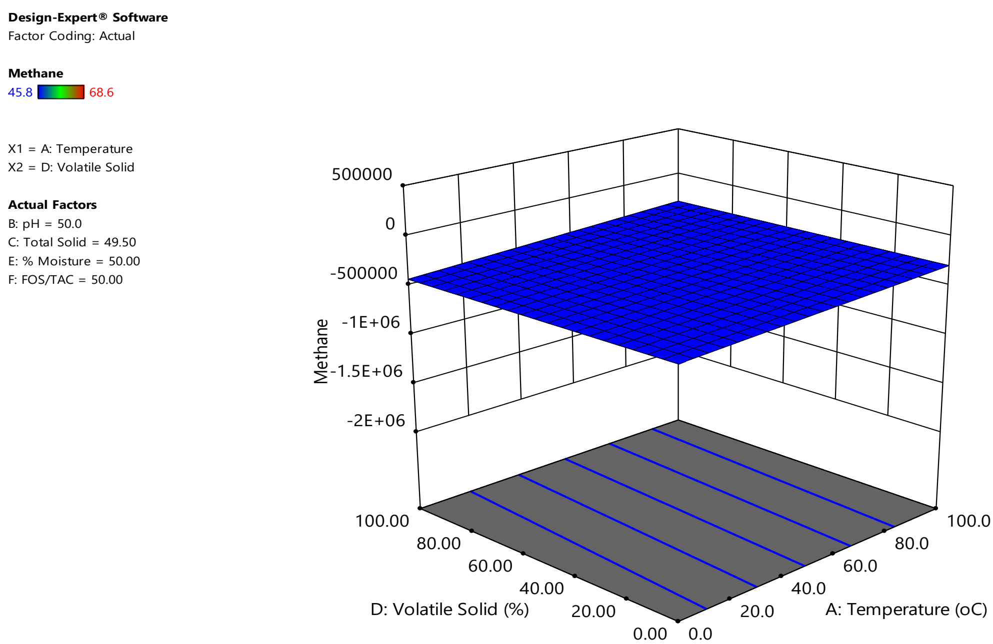

Fig. 2c. Interactive effect of volatile solid and temperature on methane yield

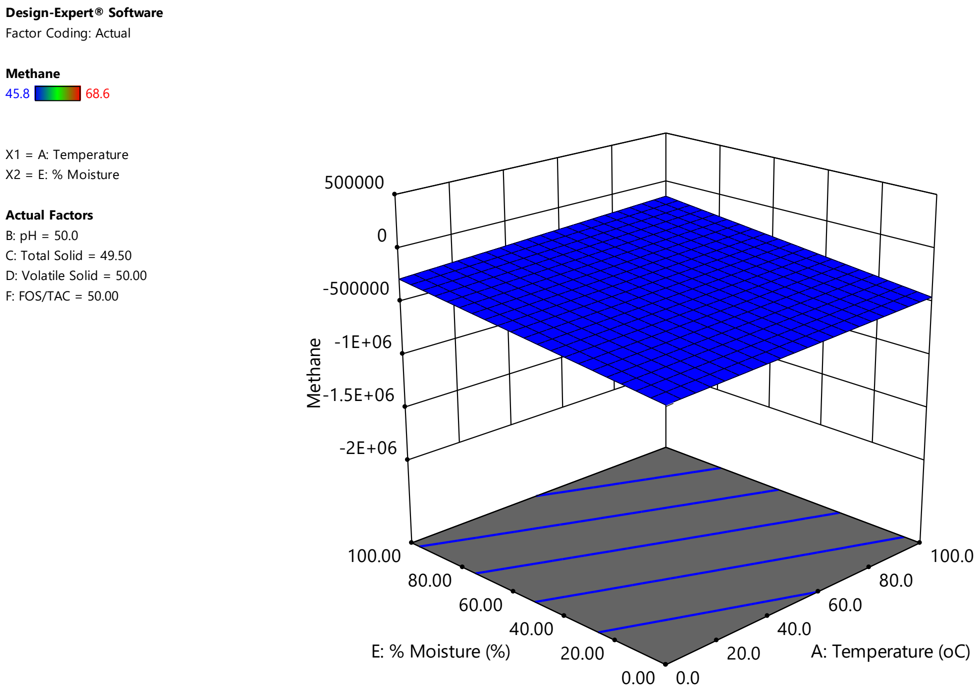

Fig. 2d. Interactive effect of moisture and temperature on methane yield

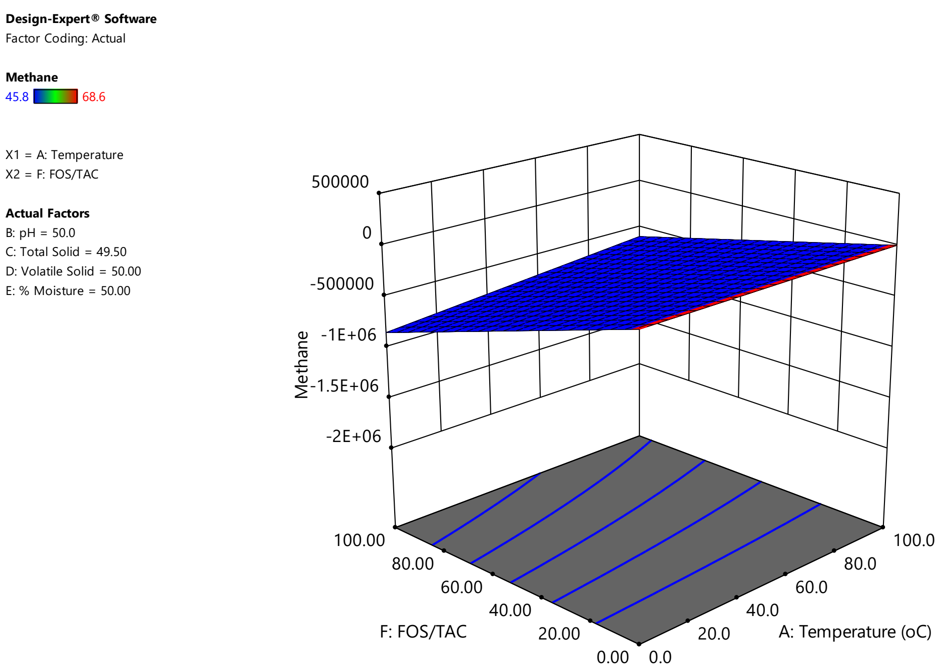

Fig. 2e. Interactive effect of FOS/TAC and temperature on methane yield

Based on the notable inconsistencies observed from the data set obtained from the biogas plant and the 3-D plots not following a regular trend, it can be deduced that the process parameters and conditions at which the AD plants operate have a significant effect on the methane yield (66.8%) which the company generates from the post digester tank. The maximum and minimum temperature recorded and observed from the data set was 40ºC and 36.2ºC respectively while maximum pH of 8.3 was recorded with 7.1 being the lowest. However, considering these factors in isolation with respect to methane yield, it cannot be said that it has a significant impact on the yield of methane. Likewise, considering the effect of Total Solid (TS) and Temperature on the yield of methane, the amount of total solid recorded was a maximum of 22% while the minimum value was 1% which still does not have much impact on the yield of methane. In the case of Volatile Solid (VS), the amount of VS added is dependent on the other parameters and from the data set, the maximum obtained was 81.60 % while the minimum was at 30.50%. Moisture on the other hand, aids the efficiency of the mixing of substrates, microorganisms and nutrients which is done by the agitators in the digestion tank and from the data set obtained, it was observed that the percentage moisture added ranges from 41.78% to 99.26% weight which was also highly influenced by weather and humidity as at the time of data collection (6months). This parameter investigated in isolation as it relates to methane yield was of minimal effect. Lastly, the FOS/TAC values obtained from the data set ranges from 0.02 to 0.26 and it cannot be said that it has a direct impact independently on the yield of Methane produced which was 66.8%. This is the major reason why optimization is a necessity in order to produce a fuel grade biogas otherwise known as biomethane. Given the consistency in the chemical properties of the substrates fed into the digester tank for a period of 6 months and optimizing the high and low values of the process parameters using an optimization software (Design Expert version 11), the optimization ramps for the optimization are presented in Figure 3 while the summary of the optimization values are presented in Table 3.

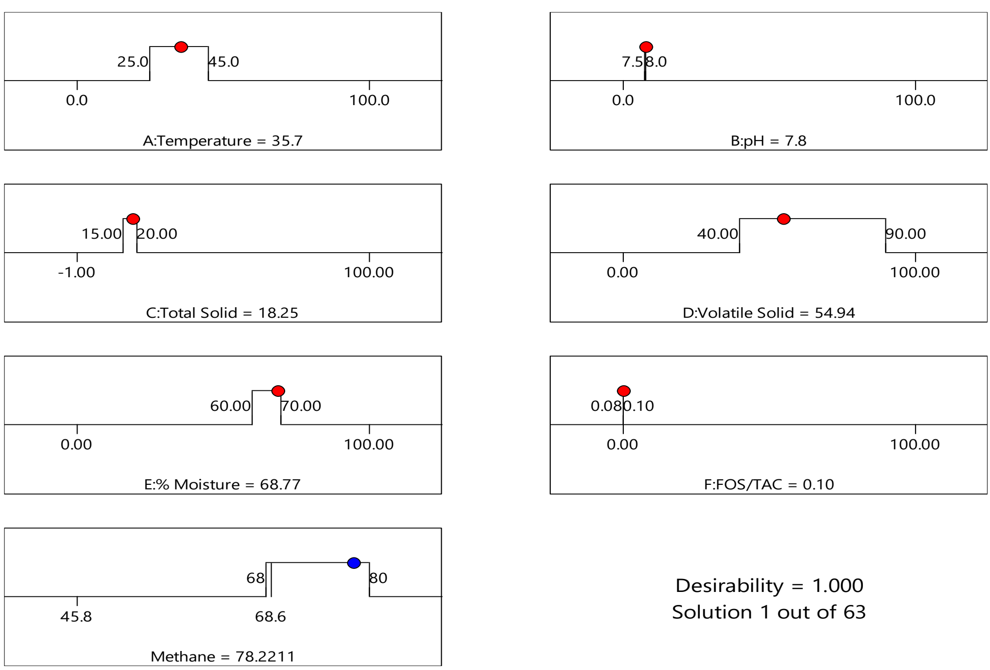

Fig. 3. Optimization ramp for process and response parameters

Table 3. Summary of optimized values for process and response parameters.

S/N	Factors	Optimized Value

1	Temperature	35.7°C
2	pH	7.8
3	Moisture	68.77%
4	Volatile Solid	54.94%
5	Total Solid	18.25%
6	FOS/TAC	0.10
7	Biomethane	78.22

From Table 3, it can be observed that optimizing the process parameters such as temperature, total solid, pH, volatile solid, moisture and FOS/TAC can lead to an increase of about 11.40% of methane (CH_4) which is a significant increase in the quality of methane given that the company currently produces biogas with 66.8% CH_4 and attaining methane content of 78.22%CH_4 (biomethane). Biomethane with methane content of 78.22% can be considered for usage as a transport fuel because it meets some countries national standards for usage as transport fuel as there is no international technical standards [32]–[34].

4 Conclusion

From the data supplied for the operating parameters of the biogas company, it can be noted that the biogas produced by the company can be upgraded to biomethane without the installation of upgrading technologies within the plant provided that the operating parameters are effectively optimized. As a result of this, the company will not only be supplying biogas for feeding into the grid, but the company will also be able to sell biomethane directly for utilization as vehicle fuel. This will enable biomethane to gradually replace the use of petroleum-based fuel such as diesel and petrol. If this is achieved, the biogas company will not only be optimizing production, but will possibly experience a drastic increase in productivity and profit, giving the company a competitive edge in the market while contributing their quota in the supply of renewable energy for both local and international consumption which is constantly in high demand.

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