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Optimization of methane biogas production using the Taguchi method: Investigating the effects of organic waste composition, solid-water ratio, and pre-treatment

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ABSTRACT

This study applies the Taguchi method to identify the key factors affecting methane biogas production and to determine optimal operating parameters for maximizing methane yield. The experimental design employed an L_4 (2^3) orthogonal array with three replications. The investigated factors included the volume-based ratio of organic waste to manure as feedstock, the volume-based dilution ratio between the mixed substrate and water, and the application of pre-treatment through conditioning of chopped organic waste. The levels of organic waste–manure composition and substrate–water composition was set at volume ratios of 30:70 and 70:30, while pre-treatment was evaluated under two conditions: conditioning of chopped organic waste by allowing it to stand for a defined period prior to digestion and no pre-treatment. The experimental results indicate that the organic waste–manure composition and the pre-treatment process have a statistically significant effect on methane biogas production, whereas the substrate–water dilution ratio shows a lower influence. Based on response table analysis, the optimal operating conditions were identified as an organic waste : manure volume ratio of 30:70, a substrate: water volume ratio of 30:70, and the absence of pre-treatment. These findings highlight the importance of clearly defining feedstock preparation and proportioning when optimizing biogas production using the Taguchi approach.

Keywords: biogas, Taguchi method, organic waste, manure.

INTRODUCTION

The escalating demand for sustainable and renewable energy alternatives has heightened scholarly interest in biogas technology as a holistic approach to energy generation and the management of agricultural waste. Methane-enriched biogas produced via anaerobic digestion presents considerable ecological advantages by mitigating greenhouse gas emissions while concurrently transforming organic by-products into valuable energy resources. Within agricultural frameworks, livestock manure and organic farming residues constitute abundant and incessant feedstocks, rendering biogas technology particularly pertinent for rural and agrarian economies [1].

Contemporary research underscores that the production of biogas from agricultural by-products aligns with circular economy principles by facilitating the closure of nutrient loops and enhancing farm sustainability. The amalgamation of manure with organic waste has been evidenced to foster microbial synergy and bolster process stability, thereby yielding enhanced methane production [2]. Moreover, farming-centric biogas systems contribute to the reduction of odors, control of pathogens, and the generation of digestate, which can be repurposed as biofertilizer, consequently augmenting the overall ecological performance of agricultural operations [3].

Nevertheless, methane biogas yield exhibits considerable sensitivity to various operational and material-related parameters. The composition of feedstock, the solids-to-water ratio, and the pre-treatment methodologies exert a significant influence on microbial activity, hydrolysis efficiency, and the overarching performance of digestion. Recent investigations focused on agricultural practices indicate that inadequate selection of these parameters may culminate in diminished methane productivity, instability of the digester, or inflated operational expenditures [4].

In this framework, the current study employs the Taguchi methodology to scrutinize the impacts of organic waste and manure composition, solids-to-water ratio, and pre-treatment processes on methane biogas production. Recent investigations have corroborated the efficacy of the Taguchi approach in optimizing parameters associated with anaerobic digestion for the production of biogas from agricultural waste and manure [5]. The methodology for generating electricity through the utilization of organic waste derived from vegetables and manure is presently being conducted based on the organic waste that is accessible. The specific composition of the vegetable and manure substrates that can yield optimal electrical energy has yet to be established. Furthermore, additional variables that may influence the resultant energy output remain unidentified. The prior investigation employed factors such as plastic content, height-to-diameter (h/D) ratio, moisture content, and duration of digestion as the experimental variables [6, 7]. Furthermore, the impact of the attributes of the input feed type and the operational parameters of the machinery, encompassing temperature and retention time, on the efficacy of this process was examined employing the response surface methodology (RSM) approach [8]. These investigations utilize experimental methodologies within controlled laboratory environments to ascertain the optimal variables. Laboratory-scale experiments frequently encounter challenges in accurately reproducing the precise conditions characteristic of industrial-scale operations [9]. The necessity for specialized apparatus, which incurs significant financial expenditure, may constrain the replicability of empirical investigations across various research facilities, thereby impeding collaborative scholarly endeavors [10, 11].

This investigation endeavors to rigorously assess the interrelations among these variables, thereby offering significant insights that may facilitate the optimization of practical conditions (Biogas production plant) to maximize biogas generation and enhance overall process efficiency. The variables employed in this inquiry include the composition of organic waste in conjunction with the manure ratio, the solids composition relative to the water ratio, and the presence or absence of pre-treatment. Through the application of the Taguchi method, this study will implement a series of meticulously controlled experiments utilizing the Taguchi approach to ascertain the most pivotal factors affecting biogas production, thereby enabling a more focused strategy for the optimization of anaerobic digestion systems.

The Taguchi method provides a systematic approach to identify the optimal conditions for maximizing biogas yield, to analyse multiple variables simultaneously and determine their influence on methane production efficiency. This approach not only facilitates the identification of key factors affecting biogas production but also encourages the adoption of innovative pre-treatment techniques that can further improve methane yield and overall process efficiency. These advancements are crucial for developing more effective strategies in renewable energy generation and waste reduction, contributing to a circular economy where organic materials are efficiently utilized. Such strategies can lead to significant reductions in greenhouse gas emissions while promoting energy independence and sustainability [12–15].

RESEARCH METHODOLOGY

Experimental research is a way to determine a causal relationship between two factors that are deliberately generated by researchers by eliminating or reducing or setting aside other disturbing factors [16–18]. The experiment was conducted in The Integrated Resource Recovery Center (IRRC) as shown in Figure 1. This research method examines several factors that affect the level energy output from organic waste, with the process of producing methane gas in this research is shown in Figure 2. The substrate used in this study consisted of chopped vegetable waste and manure. The vegetable waste was composed primarily of cabbage (*Brassica oleracea*) and Chinese cabbage (*Brassica rapa* pekinensis) obtained from local markets. Prior to digestion, the vegetable waste was manually chopped into small pieces (approximately 1–2 cm) to improve homogeneity. The manure used in this study was fresh cattle manure, collected from a local livestock farm and used without further treatment. The steps of producing methane biogas are collecting organic waste from vegetables, refining

Figure 1. The facilities of waste handling for bio-energy from organic waste

process, pre-treatment (optional), weighting, mixing and covering the inlet tank.

The research was carried out through preliminary stages, experiment design, experiment, data processing and analysis. The identification of input signals, noise variables, control parameters, and error conditions pertinent to the optimal function that using P-diagram was conducted as the preliminary stage of this research. The P-diagram utilized in this study is illustrated in Figure 3. This diagram encompasses variables such as the category of organic waste, the pH level of the mixture, the temperature of the mixture, the moisture content, the C/N ratio, the mixing methodology, the composition of organic waste in conjunction with manure, the solid composition in relation to water, and the pre-treatment process.

The experiment design by using Taguchi method was started from the orthogonal matrix determination. The orthogonal matrix was chosen based on the number of factors and levels, and the degrees of freedom value as a reference of the minimum experiments. The value of the degrees of freedom in the orthogonal array must be greater than the value of the degrees of freedom of the research being carried out. The degrees of freedom in this study are 3, so the orthogonal array that has a degree of freedom value greater than 3 is closest to $L_4(2^3)$ with a degree of freedom value of 4. By using the $L_4(2^3)$ matrix, 4 experiments will be carried out with combinations factors as in Table 1.

Calculation of the level effect of factors on the average response variable

At this stage, the calculation of the influence of factors on the average response variable is carried out. Then an analysis of variance (ANOVA) was performed on the average kilowatt per hour (kWh) for each factor. Doing pooling up on the factor that has the least squared sum value. The calculation of the percentage contribution value is carried out to determine the effect of each factor. Calculation of confidence intervals for the predictive value of the influence of factors on the average response variable.

Calculation of the level effect of factors on the variability (S/N) of the response variable

At this stage, the calculation of the effect of the factors on the S/N ratio on the response variable is carried out. Then an ANOVA was performed on the average value of the S/N ratio for each factor. Doing pooling up on the factor that has the least squared sum value. The calculation of the percentage contribution value is carried out to determine the effect of each factor. Confidence interval calculation for the predicted value of the influence of the factor on the S/N ratio on the response variable.

RESULTS AND ANALYSIS

Methane gas produced during the anaerobic digestion process was released from the biodigester and initially passed through a pressure gauge installed at the gas outlet. The pressure gauge was used to monitor the gas pressure generated inside the digester, which served as an indicator of methane gas production. After pressure measurement, the gas was subsequently channelled into a flexible gas storage balloon for temporary storage. The methane production data were obtained by recording the pressure values at regular intervals under consistent operational

Figure 2. Process of producing methane gas in IRRC

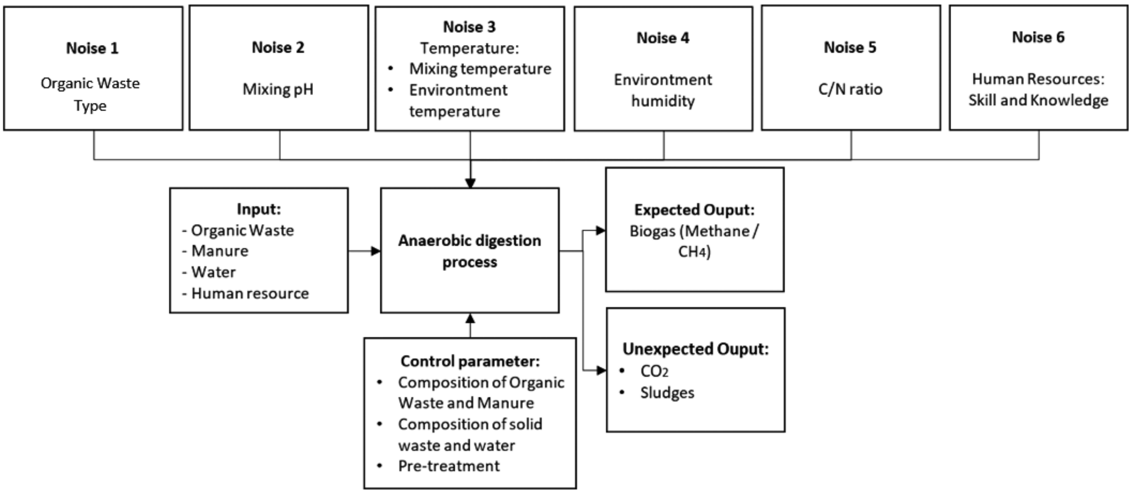

Figure 3. The P-diagram of research experiment design

Table 1. Experiment design with factor and level factor

Code	Control factor	Level factor	
		1	2
A	Composition of organic waste and manure	30:70	70:30
B	Water composition	30:70	70:30
C	Pretreatment	No treatment	2 days

conditions. These pressure readings were used as a relative measure of methane output for comparative analysis among experimental runs in the Taguchi experimental design. The data collection for the experiment was conducted by observing the numbers on the flowrate meter after 5 days of experimentation, then subtracting the initial flowrate meter reading at the beginning of the experiment as shown in Table 2. The noise factors measured for correlation calculations include the pH of the mixture, ambient temperature, and humidity levels. The pH of the mixture is determined using a digital pH meter, while the ambient temperature and humidity readings are obtained from a weather application. Table 3 are the recorded values of the noise factors throughout the experiment.

The data analysis pertaining to the experimental study is segmented into three distinct components: the assessment of the mean output

Table 2. The initial flowrate of output of methane (m3)

Experiment	Factor			Output biogas methane (m^3)		
	A	B	C	Y1	Y2	Y3
1	1	1	1	3.808	4.3288	4.0488
2	1	2	2	3.4366	3.1198	3.5836
3	2	1	2	3.0006	3.5476	3.183
4	2	2	1	3.1704	3.7184	3.2642

Table 3. Noise factor throughout the experiment

Experiment day	Noise factor		
	pH (mixed)	Environment temperature (˚C)	Humidity (%)
1	6.68	24	84
2	7.28	23	90
3	6.86	24	76
4	7.2	24	86
5	7.02	25	83
6	7.2	24	79
7	7.11	23	85
8	7.56	24	82
9	7.6	25	83
10	6.77	26	80
11	7.3	23	81
12	7.56	23	83

Table 4. The average of methane biogas output

Level	Factor		
	A	B	C
1	3.721	3.653	3.723
2	3.314	3.382	3.312
Difference	0.407	0.271	0.411
Rank	2	3	1

of methane biogas, the evaluation of the signal-to-noise ratio associated with methane biogas, and the investigation of the correlation between noise determinants and the output of methane biogas.

Based on the experimental findings, a response matrix was constructed to identify the levels of influencing factors and the specific variables that affect the mean output of methane biogas. The average of methane biogas output is shown in Table 4.

By analysing these factors, we can fine-tune the processes to enhance biogas yield and reduce costs, ultimately leading to more sustainable energy production. Average Output of Methane Biogas From the results of the experiment, a response table was compiled to determine the levels of factors and the factors that influence the average output of methane biogas. Based on Table 4, factor B, which is the composition of solids with water, is indicated to have the smallest impact value on the output of methane biogas. The factor levels for producing optimal average methane biogas are identified, allowing for a clearer understanding of how varying compositions affect the overall efficiency and yield of biogas production. Subsequently, an ANOVA was conducted to assess the extent to which the identified variables exert a statistically significant effect on the mean production of methane biogas, as shown in Table 5.

The Table 5 shows that the calculated factors are 6.91 for factor A (the composition of organic waste with manure), 3.06 for factor B (the composition of solids with water), and 7.06 for factor C (pre-treatment). From the F test results, factors A and C have an F value greater than the F table (F0.05;1;8) = 5.32, which indicates that factors A and C significantly influence the output of methane biogas. In contrast, factor B does not have a significant effect, as evidenced by its F value being below the critical threshold. This finding underscores the importance of optimizing factors A and C to enhance methane production efficiency. Therefore, the pooling up of factor B is need to be carried out. The calculation for pooling up result is shown in Table 6.

Following the aggregation of data, the findings indicate that the F-value computed for factors A and C exceeds the critical value from the F-distribution table (F(0.05;1;8) = 5.32), thereby suggesting that the compositional parameters of organic waste combined with manure and subjected to pre-treatment exert a statistically significant influence on the yield of methane biogas. The factor that contributes the most substantially is factor C, accounting for a

Table 5. ANOVA of the mean of methane biogas output

Factor	Df	SS	MS	F_{count}	SS'	%
A	1	0,469	0,4967	6,91	0.4248	23.61
B	1	0,219	0,21973	3,06	0.1478	8.21
C	1	0,507	0,50734	7,06	0.4354	24.20
Error	8	0,575	0,0719	1	0.7909	43.96
SSt	11	1,798			1.7989	100
Mean	1	148.4723				
SS_{total}	12	150.2712				

Table 6. The ANOVA of pooling up result of methane biogas output

Factor	Df	SS	MS	F_{count}	SS'	%
A	1	0.469	0.4967	5.6238	0.4084	22.70
B	*Pooled*					
C	1	0.507	0.50734	5.7442	0.4190	23.29
e_{pooled}	9	0.7949	0.0883	1		54.01
SSt	11	1.798			1.7989	100
Mean	1	148.4723				
SS_{total}	12	150.2712				

contribution percentage of 23.29%, while factor B follows closely with a contribution of 22.70%. This analysis underscores the critical role of these factors in the optimization of biogas production, implying that modifications to their respective ratios may substantially enhance the overall methane output. The factors that strongly influence methane biogas output, namely C_1 and A_1, are as follows:

$$\mu_{pr} = \bar{y} + (\overline{C_1} - \bar{y}) + (\overline{A_1} - \bar{y}) \quad (1)$$

$$\mu_{pr} = 3.52 + (3.72 - 3.52) + (3.72 - 3.52) = 3.93 \text{ m}^3$$

$$n_{eff} = \frac{no.\ of\ tot.\ exp.}{1+no.\ of opt.\ deg.\ of\ freedom} = \frac{4\times3}{1+(1+1)} = 4 \quad (2)$$

The calculation of the confidence interval for factors that influence the average methane biogas output as follows, where n_{eff} is number of effective observations.

$$CL = \sqrt{\frac{F_{(0,05:1:8)}(MS_{error})}{n_{eff}}} = \sqrt{\frac{(5,32)(0,088)}{4}} = 0.34 \quad (3)$$

Thus, the confidence interval is:

$$\mu_{prediction} - CL_p \leq \mu_{prediction} \leq \mu_{prediction} + CL \quad (4)$$
$$= 3.58385 \leq 3.92655 \leq 4.26925.$$

The methane biogas output has "the larger the better" characteristic where the higher the volume value of methane biogas, the better. The calculation of the S/N ratio is shown in Table 7. The response table for determining the factor levels and factors that influence the variability of methane biogas output is shown in Table 8.

According to Table 8, factor B, namely the composition of solids with water, is indicated to have the smallest influence value on methane biogas output. The factor levels to produce optimal methane biogas output variability are A_1, B_1, and C_1. Hereafter, the ANOVA calculations were carried out to determine the significant factors that affect the variability of methane biogas output, as shown in Table 9.

The percentage contribution value in Table 9 shows that the factor with the largest percentage contribution is factor A with a value of 25.8145% and followed by factor C with a value of 25.2843%. It was found that there were no factors that strongly influenced the reduction of methane biogas output variance. The equation model that will be formed for methane biogas output variance as follows:

$$\frac{S}{N_{pmbo}} = \bar{y} + (\overline{A_1} - \bar{y}) + (\overline{C_1} - \bar{y}) = (10.84) +$$
$$+(11.34 - 10.84) + (11.33 - 10.84) = 11.83\ m^3 \quad (5)$$

Table 7. S/N ratio of larger the better

Experiment	Factor			S/N ratio
	A	B	C	
1	1	1	1	12.13888
2	1	2	2	10.53412
3	2	1	2	10.15884
4	2	2	1	10.52786

Table 8. The response table of methane biogas S/N ratio

Level	Factor		
	A	B	C
1	11.337	11.149	11.333
2	10.343	10.531	10.346
Difference	0.993	0.618	0.987
Rank	1	3	2

With the calculation of the confi dence interval is:

$$S/N_{predition} - CL_p \leq S/N_{prediction} \leq S/N_{prediction} + CL_p = = 11.1173 \leq 11.8299 \leq 12.5425.$$

According to the experiment result and analysis, it is evident that the optimal factor levels for maximizing methane biogas output are established at level 1 for each variable: a 30:70 ratio pertaining to the composition of organic waste relative to manure, a 30:70 proportion for solids to water, and the absence of any pre-treatment. Regarding the organic waste-to-manure variable, the 30:70 ratio yielded a superior methane biogas output in comparison to the 70:30 ratio. One rationale for this phenomenon is the prevalence of anaerobic digestion bacteria within the digester dome; an excess of organic waste in relation to bacteria can hinder and render the anaerobic digestion process less efficient. With an elevated bacterial population in proportion to organic waste, the anaerobic process accelerates, resulting in increased methane biogas production.

For the solids-to-water ratio, the 30:70 configuration produced greater methane biogas output than the 70:30 configuration. This outcome can be attributed to the pivotal role of water content in the anaerobic digestion process. A reduction in water content within the mixture leads to a concomitant decrease in the population of active anaerobic bacteria. Concerning the pre-treatment variable, the absence of pre-treatment resulted in a higher methane biogas output than its application. This finding deviates from earlier investigations on the effects of pre-treatment, potentially due to differences in the pre-treatment methodologies employed in prior controlled laboratory studies. In the context of the IRRC, the pre-treatment methodology proves to be less efficacious, as organic waste is subjected to open-air exposure to solar radiation. The diagram of main effect of mean and S/N ratio are shown in Figure 4.

The percentage contribution of error in the ANOVA calculation for average methane biogas output surpassed 50%, reaching a value of 54.01%. This finding implies that, even after pooling, there exist additional variables influencing the average methane biogas output that were neither acknowledged nor incorporated into the experimental design. Furthermore, a substantial error contribution percentage may signify the influence of noise factors or uncontrolled variables affecting the experimental outcomes.

Table 9. ANOVA for factors that affect the variability of methane biogas output

Asal	Df	SS	MS	F_{hitung}	%
A	1	0.98635	0.98635	1.2634	25.8145
B	*Pooled*				
C	1	0.9739	0.9739	1.2475	25.2843
e_{pooled}	1	0.3818	0.3818	1	48.9012
SSt	3	2.3421			100
Mean	1	470.0161			
SS_{total}	4	472.3581			

In the S/N ratio response table analysis for methane biogas output, the optimal factor levels were similarly situated at level 1 for each factor: a 30:70 proportion for organic waste to manure, a 30:70 ratio for solids to water, and no pre-treatment, which aligns with the average methane biogas output calculations.

ANOVA findings for the methane biogas S/N ratio indicated that Factor B was directly pooled due to its negligible effect on methane biogas output. Factor A accounted for 25.8145%, Factor C contributed 25.2843%, and the error factor contributed 48.9012%. This is deemed acceptable, as the error contribution percentage remains below 50%, signifying that the significant variables influencing variance were adequately represented within the experimental framework. The findings, when juxtaposed with the initial conditions, exhibited minimal variation. This phenomenon can be attributed to the fact that the initial conditions, prior to the commencement of data recording, closely mimicked the optimal parameters for the anaerobic digestion process, characterized by an excess of manure relative to organic waste, a greater volume of water compared to the mixture, and the absence of any pre-treatment protocols. Nevertheless, the outcomes of this experiment may serve to motivate operators to maintain a higher degree of consistency in executing anaerobic digestion practices, thereby optimizing methane biogas production.

Furthermore, a contributing factor to the suboptimal outcomes of this experiment is the execution of the study in a field setting. This has resulted in a pronounced impact from extraneous noise factors, alongside a limited number of controllable variables during the experimental process. Should the experiment be conducted within a more regulated environment, such as a laboratory, the findings may reveal a more pronounced disparity. However, it is worth noting that the applicability of laboratory-derived results in practical field conditions may be hindered by variations in the instruments or contextual factors employed.

The pre-treatment factor presents discrepancies when compared to the findings of preceding studies. To enhance both the yield and quality of the methane biogas, alternative pre-treatment methodologies warrant consideration. One potential approach involves the utilization of a heater to maintain a relatively stable temperature of the mixture prior to its introduction into the dome digester. The optimal temperature settings for the heater can be determined by taking into account the ambient temperature and the volume of water utilized, thereby ensuring a consistent mixture temperature within the dome digester. The operation of this heating apparatus could be facilitated by electricity generated from the methane biogas itself.

Moreover, the incorporation of additives into the anaerobic digestion process has the potential to augment methane biogas production. The introduction of minor quantities of chemicals, such as iron salts or nickel, can lead to a significant increase in biogas yield. However, challenges persist in procuring these chemicals and ensuring that the scales employed yield precise chemical measurements as required.

The implementation of a filtration mechanism within the IRRC may enhance the quality of the methane biogas generated. Typically, methane biogas produced from anaerobic digestion contains a methane concentration ranging from 50–60%. By instituting a filtration process, non-methane components can be diminished,

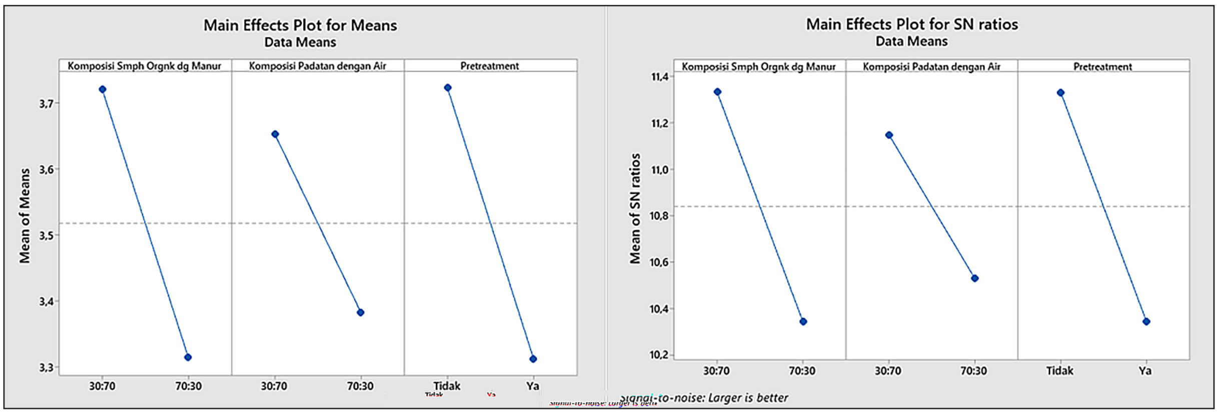

Figure 4. The diagram of main effect of mean and S/N ratio

resulting in a more concentrated methane output. This purified biogas could subsequently serve multiple purposes, not only as a source of electricity but also as a replacement for domestic gas or as a commodity.

CONCLUSIONS

It can be inferred that two primary factors exert a substantial influence on the production of methane biogas, specifically the pretreatment process and the composition of organic waste in conjunction with manure. This assertion is substantiated by the percentage contributions derived from the ANOVA analysis post-pooling, which quantify at 23.29% for factor C (pretreatment) and 22.7% for factor A (composition of organic waste with manure). The identification of optimal factors and their corresponding levels for methane biogas production is facilitated by the response table of variable data, wherein the sought-after characteristics are characterized by a preference for maximization; specifically, factor A at level 1 (30:70), factor B at level 1 (30:70), and factor C at level 1 (absence of pretreatment).

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