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Multi Objective Optimization of Anaerobic Digestion of Poultry Litter Using Taguchi Grey Relational Analysis

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Abstract

This study emphasis the biogas production through anaerobic digestion of poultry litter were investigated by applying four factor-four level Taguchi design under experimental conditions such as pH (7.2–7.8), temperature (25-28°C), solid concentration (9.5%–21.5% TS) and C/N (15.1-15.4) .L16 orthogonal array was formulated for selected process parameters using Taguchi design of experiments (DOE) and the Digestion process were carried in fixed dome batch reactor under a hydraulic retention time of 21 days. The output responses and their signal-noise are measured Multi-objective technique grey relational analysis (GRA) were used to determine the optimal level of process parameters. The optimum level values of process parameters obtained for anaerobic digestion of pretreated poultry litter is solid concentration of 13.5% TS, pH of 7.4, temperature of 26 °C and C/N 15.3 respectively. Obtained results were analyzed by analysis of variance and the percentage contributions of each parameter were determined. The result from ANOVA showed that Solid Concentration is the most influential factor due to its higher percentage contribution (42.41%) among the process parameters, which is followed by pH 23.08 %, C/N 16.19 % and temperature by 5.59 %. The biogas yield can be improved in a better way by fixing the derived optimum condition.

Keywords: Anaerobic Digestion, Biogas, Poultry Litter, Grey Relational Analysis

INTRODUCTION

In recent times climate change is certainly the most imminent environmental issue in the world. The raise in the global mean temperature have certain effects on the ecosystem, wildlife, food chains and eventually human life[1]. And there is a consensus that global warming is due to the large scale anthropogenic emission of greenhouse gases, which are mainly caused by the generation of heat and power. Indeed, still a large fraction of the global energy demand is satisfied through the use of fossil fuels[2]. According to the survey of International Energy Agency (IEA), fossil fuels accounted for up to 80% of the world’s primary energy supply in 2016 whereas renewable energy sources only contributed a mere 15%[3]. More attention is being paid to the implementation of renewable energy sources, worldwide fossil fuels will remain the most dominant energy source, estimated at 77% for the period 2016–2030[3].This small decrease in the total share will be largely compensated by the expected 2.5% annual rise in energy demands until 2030. Most of the increase will be realized by a higher consumption of coal, followed by gas and oil[4].

It is clear that renewable resources will play a crucial role in the CO_2-mitigation[5]. In this regard, energy from biomass and waste is seen as one of the most dominant future renewable energy sources, especially since that a continuous power generation from these sources can be possible, unlike other types such as solar energy and wind energy[6]. Waste materials like sewage sludge, animal manure and, crop wastes are available widely for the generation of energy. Techniques like thermochemical, biochemical and physicochemical conversion processes are available for power generation from the organic biomass and waste[3]. In recent years, the application of anaerobic digestion for the treatment of organic waste has emerged spectacularly and the attractiveness is due to the various beneficial properties of the process. The produced biogas consisting of 65% CH_4, 35% CO_2 and trace gases such as H_2S, H_2 and N_2 is energy efficient and environmentally friendly because of the low emission of hazardous pollutants, the biogas can be upgraded to natural gas purity[7] .The produced slurry (digestate) is nitrogen rich and can in most cases be utilized in agriculture as a nutritive fertilizer and organic amendment[7]. A more novel application is to transform the digestate into bio char, which can be further employed as soil enhancer or an adsorbent for purification of wastewater or flue gas.

Poultry farming is one of the fastest growing segments of the agricultural sector in India with around eight percent growth rate per annum. The increase in poultry population results in high amount of poultry litter daily, which needs to be managed[8]. If this manure is untreated or poorly managed, it can cause air and water pollution as well as the emissions of CH4 that cause global warming. On the other side when handled properly, manure can be used as a renewable energy source[9]. Anaerobic digestion process serves as a waste stabilization while simultaneously generating renewable energy, thus acts as an important part of sustainable waste management.

The major limitation of using PL for biogas production is its low C/N ratio, which is around 5–8[10]. Substrates with low C/N ratio during the anaerobic digestion tend to accumulate ammonia, which is toxic to the anaerobic micro flora. Higher

C/N ratios result rapid Nitrogen consumption by methanogens, which results in nutrient deficiency and lower methane yields[11]. Low C/N ratios lead the accumulation of ammonia and increase in pH, which are toxic to methanogenic bacteria. In anaerobic digestion process, the recommended range for C/N ratio is between 15 and 30 and C/N ratio of 25 is used commonly[11]. C/N ratio of a substrate shows its nutrient levels. In order to obtain a proper C/N ratio, feedstock containing low C/N ratio can be pretreated to improve its C/N ratio. A number of methods available to increase the C/N of the feedstock in order to mitigate the ammonia nitrogen produced inside the digester. Among various methods ammonia volatilization found to be suitable for large scale application.

The effective production of biogas and biodegradation of organic matter highly depends on the involvement of various process parameters such as solid concentration, pH, temperature, C/N ratio, etc.[12]. Optimization of the above process parameters is essential for effective gas production. The most common and widely used techniques to optimize the parameters are simplex method, Response Surface Method (RSM), Genetic Algorithm (GA), Artificial Neural Network (ANN), Taguchi method, Grey Relational Analysis (GRA), etc.[13][14]. Among this techniques Grey relational analysis (GRA) is a technique mainly employed to convert multi objective problem into a single objective and used to identify the optimal combination of process parameters that maximize the biogas yield and volatile solid removal rate[14].

The main objective of this work is to enhance the biogas yield by increasing the C/N of the feedstock by using ammonia volatilization pretreatment method and to find an optimal condition for better biomethanation of pretreated PL by using Taguchi based Grey relational analysis.

MATERIALS AND METHODS

Production of biogas from poultry litter by anaerobic digestion was performed using lab scale fixed dome type batch reactors. The process parameters are identified that affect the biogas yield and Volatile solid removal rate for experimentation and afterwards the procedure of research methodology has been designed. Based on designs from Taguchi's DoE, experiments were performed. By applying the hybrid technique of Taguchi-GRA and statistical tool ANOVA, results are analyzed. The methodology applied in this work is given in the flow chart and are shown in **Figure 1.**

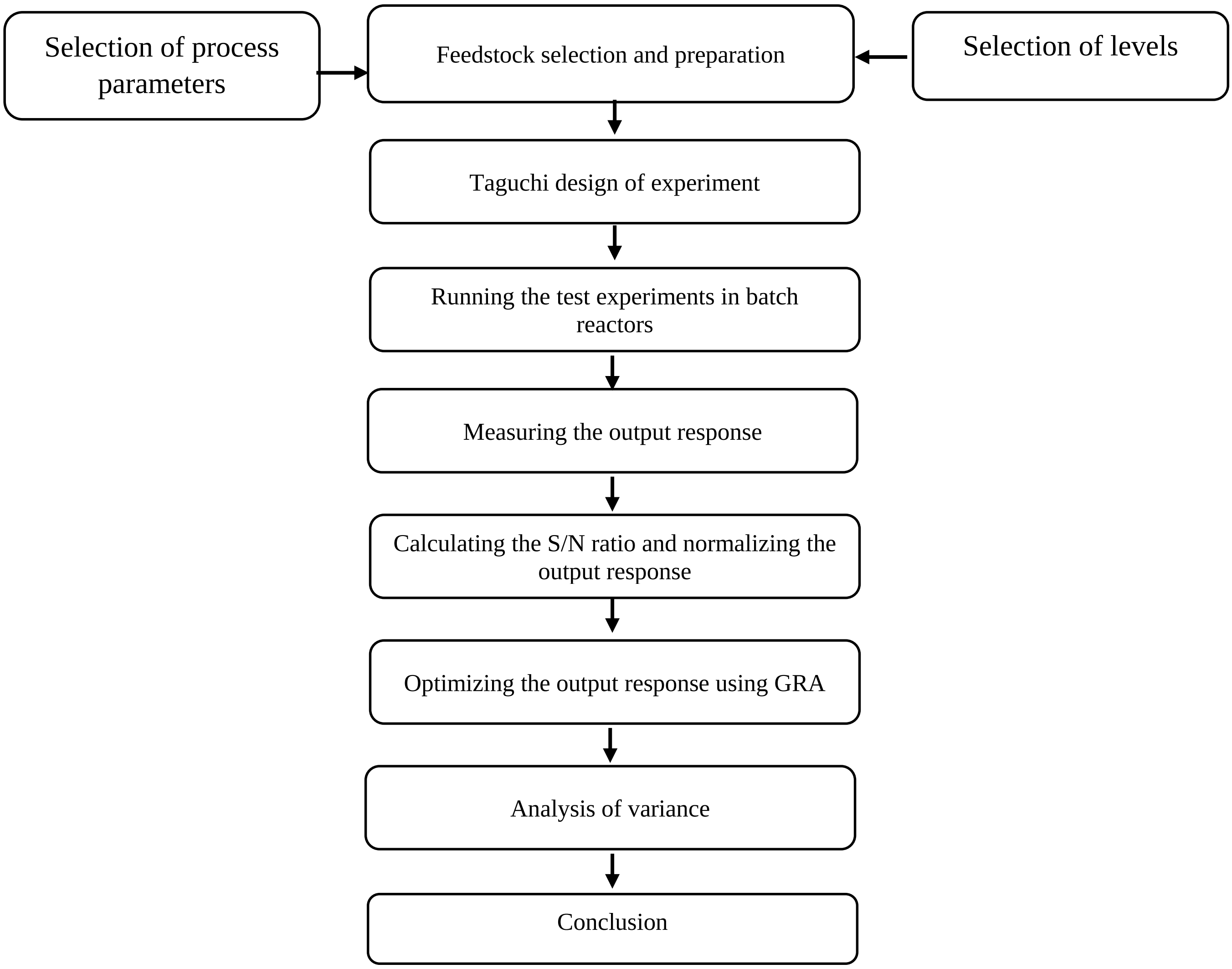

Figure 1. Methodology of the work

Analytical methods

The total solids (TS), volatile solids (VS), fixed carbon and pH of the substrate were determined as per the standard methods. The pH of the substrate was determined using digital pH meter. For calculating the TS, every day the samples are taken out and dried in the hot air for 1 hour at 105℃ .after that ratio between the dried samples to wet sample values are noted down[15]. The Total Kjeldahl Nitrogen (TKN) of the feedstock was estimated using the Kjeldahl Method by standard procedures[8][16]. The test is performed to find out the nitrogen concentration in the slurry.

Experimental setup

Laboratory scale fixed dome batch digesters were used to carry out the experiments. The reactor was made of polyethylene terephthalate PET with a volume of 20 liters is equipped with all measuring instruments. The schematic view of anaerobic reactor used for the experimentation is shown in **Figure 2.** The digestion was carried out at mesophilic condition of 25 – 30 ℃ and pH is maintained at near neutral range. The biogas volume produced from the batch digester was determined using a positive displacement Gas flow meter.

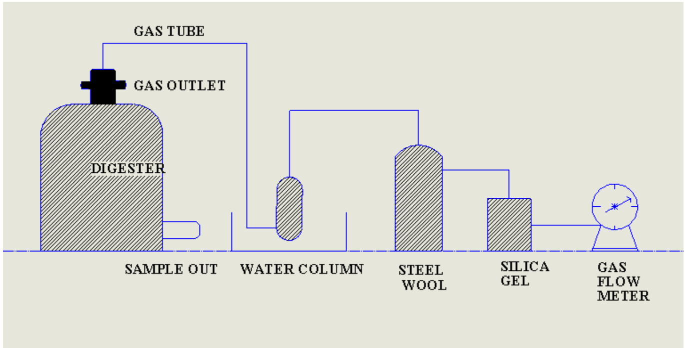

Figure 2. Experimental setup of anaerobic digestion

Pretreatment carried out

To increase the biogas yield during the anaerobic digestion process, the C/N ratio should be in the optimal value. For bring the optimal range the poultry litter should undergo ammonia volatilization pretreatment process. The ammonia volatilization pre-treatment consists of a first anaerobiosis phase of about 60 days[8]. During this days the poultry waste is dumped in air tight conditions without any treatment under room temperature, most of the protein and uric acid in the wastes are converted to nitrogen and ammonia. And after anaerobiosis, the feedstock is heated to about 80 °Cfor a period of 24 hours in aerated condition[8]. And finally the treated samples were loaded into the digester for the anaerobic digestion process.

Taguchi design of experiments

L16 Orthogonal array with different combinations of input parameters were designed by using mini tab 17 to carry out experimental work[17]. Taguchi's DoE is applied in this work for the experimental array design while considering four parameters viz., solid concentration, pH, temperature and C/N ratio. Individual parameters are varied through four levels as given in **Table 1.**

Table 1. Experimental parameters with levels

Sl.no	Parameter	Symbol	Level 1	Level 2	Level 3	Level 4
1	pH	A	7.2	7.4	7.6	7.8
2	Temperature (℃)	B	25	26	27	28
3	Solid Concentration (%)	C	9.5	13.5	17.5	21.5
4	C/N	D	15.1	15.2	15.3	15.4

The inner L16 orthogonal array formulated for the chosen parameters and their level values are given in **Table 2.**

Grey relational analysis

In GRA, the measured output values for analysis are initially normalized between zero and one, called grey relational generation. After normalizing the values the grey relational coefficient is found, which represents the correlation between the desired and actual experimental values[18]. By taking the average of calculated grey coefficients, overall grey relational grade is calculated for respective output responses. Hence, a multi response problem is converted into a single response process optimization problem with grey relational grade (GRG).

Eq. (1), ''larger-the-better condition'' is applied when the expected data sequence is maximum

$$x_i^*(k) = \frac{x_i^\circ(k) - min\, x_i^\circ(k)}{max\, x_i^\circ(k) - min x_i^\circ(k)} \qquad (1)[17][19]$$

Eq. (2) is used for normalizing when the response data sequence is in the form ''smaller-the better''

$$x_i^*(k) = \frac{max\, x_i^\circ(k) - x_i^\circ(k)}{max\, x_i^\circ(k) - min x_i^\circ(k)} \qquad (2)[17][19]$$

Where x_i^* (k) is normalized value, original sequence is $x_i^\circ(k)$, $max\, x_i^\circ(k)$ is the largest value of $x_i^\circ(k)$ for the k[th] response and $minx_i^\circ(k)$ the smallest value of $x_i^\circ(k)$. i is the number of experiments (i = 1, 2, 3 . . .) and k is the number of responses (k = 1, 2, 3 . . .).

Next, grey relation coefficient (GRC) is calculated to identify the relationship between the reference sequence and actual sequence. The GRC can be calculated using the following equation

$$\zeta_i(k) = \frac{\Delta min + \zeta.\Delta max}{\Delta_{oi}(k) + \zeta.\Delta max} \qquad (3)[17][19]$$

Where Δ_{min} is the smallest value of $\Delta_{oi}(k)$, ζ is the distinguishing coefficient whose value is considered as ζ [0, 1], normally used value is ζ = 0.5 and Δmax is the largest value of $\Delta_{oi}(k)$ [19].From grey coefficient, grey grade is calculated by averaging the coefficient for each level of inputs.

Table 2. Formulated L16 inner orthogonal array, measured output response and their S/N ratio

Trail No	pH	Temperature	Solid concentration	C/N	Measured Output Responses		S/N Ratio	
					Biogas Yield Kg	VSRR	Biogas Yield Kg	VSRR
1	7.2	25	9.5	15.1	1.1681	55.9500	1.3496	34.9560
2	7.2	26	13.5	15.2	2.0774	74.9100	6.3504	37.4908
3	7.2	27	17.5	15.3	2.3832	63.0100	7.5432	35.9882
4	7.2	28	21.5	15.4	1.8642	69.2100	5.4099	36.8034
5	7.4	25	13.5	15.3	2.8670	66.0100	9.1486	36.3922
6	7.4	26	9.5	15.4	2.4450	69.4200	7.7656	36.8297
7	7.4	27	21.5	15.1	1.5580	84.6800	3.8513	38.5556
8	7.4	28	17.5	15.2	1.6960	72.6200	4.5885	37.2211
9	7.6	25	17.5	15.4	1.2163	75.2600	1.7008	37.5313
10	7.6	26	21.5	15.3	2.3438	75.7400	7.3984	37.5865
11	7.6	27	9.5	15.2	1.0681	52.6920	0.5722	34.4349
12	7.6	28	13.5	15.1	2.3292	80.2000	7.3441	38.0835
13	7.8	25	21.5	15.2	1.2254	72.0100	1.7656	37.1479
14	7.8	26	17.5	15.1	1.2201	64.1352	1.7279	36.1419
15	7.8	27	13.5	15.4	2.5275	59.1700	8.0538	35.4420
16	7.8	28	9.5	15.3	1.8179	70.5942	5.1914	36.9754

GRG gives information about the relationship among the sequences. Its value lies in the range of 0 to 1.In this present study, the biogas yield and volatile solid removal rate are to be maximized, for which larger-the-better formula is selected for normalizing.

RESULT AND DISCUSSION

After performing the experiments with the designed L16 orthogonal array, experimental trials were carried out and the corresponding output responses value are noted as given in from the **Table 2.** The observed values shows that, when the pH value of the substrate increased from 7.2 to 7.4 the biogas production and VSRR increased by 14.32% and 11.27 % respectively. With further increase of pH value from 7.4 to 7.6 the biogas yield and VSRR decreased by 18.77% and 3.01%.A decrease in biogas yield and VSRR by 2.39% and 6.33% were obtained, when the pH was increased from 7.6 to 7.8. The result shows that pH of the substrate influence the activities of acidogenic bacteria and methanogen during the whole process and also it affect hydrolytic and acetogenic step of the digestion process, therefore it affects the biogas yield and decomposition rates of poultry litter. This series of experiment study clearly demonstrated that the pH 7.4 were most suitable initial pH for anaerobic digestion of poultry litter.

An increase in biogas production by 24.85% was observed while raising the temperature from 25 ℃ to 26 ℃ along with increase in VSRR by 5.56% respectively. While increasing the temperature from 26 ℃ to 27℃, decrease in biogas production by 6.79% and VSRR by 8.67% were obtained. Further increase in temperature from 27 ℃ to 28℃ increased the biogas production and VSRR by 2.26% and 12.74% respectively. This results implicate that the activity of the methanogenic bacteria used in this study can grow effectively in the mesophilic condition at 26℃. The temperature fluctuation are very sensitive to the bacterial growth, so it is necessary to maintain a constant temperature. Microbial growth rates and free ammonia nitrogen(FAN)concentration are affected by the temperature change during the AD process. An increase in temperature of AD commonly increases the metabolic rate of the microorganisms but also results in a higher concentration of FAN this affects the biogas production rate.

When the solid concentration of the substrate were increased from 9.5% to 13.5%, increase in biogas yield by 50.8% and VSRE by 12.72% were noticed. A decrease in biogas yield by 33.52 % and VSRE by 1.87% were observed when the solid concentration was changed from 13.5% to 17.5% of TS. With further increase in solid concentration from 17.5 % to 21.5%, an increase in biogas yield by 7.30% and VSRE by 9.67 % were obtained. This was due to the abundant availability of readily biodegradable materials present in the substrate. After 13.5% of total solids, the biogas yield and VSRR decreased with respect to solid concentration, because of poor microbial/enzymatic substrate contact with increased amount of substrate present in the digester.

A decrease in biogas production by 3.32% and VSRE by 4.47% were noticed, when the C/N ratio of substrate was increased from 15.1 to 15.2. Further increase in C/N ratio from 15.2 to 15.3 increased the biogas production and VSRE by 55.13 % and 1.14% respectively. The lower biogas production was achieved beyond C/N ratio of 15.3, which is probably due to inhibition of releasing ammonia during the degradation process and also because of low biodegradability.

Table 3. Normalizing, deviation sequence for output responses and grey relational grade

Sl.no	Normalizing Sequence		Deviation Sequence		GRC		GRG
	Biogas	VSRR	Biogas	VSRR	Biogas	VSRR	
1	0.0906	0.1265	0.9094	0.8735	0.3548	0.3640	0.3594
2	0.6737	0.7416	0.3263	0.2584	0.6051	0.6593	0.6322
3	0.8128	0.3769	0.1872	0.6231	0.7276	0.4452	0.5864
4	0.5641	0.5748	0.4359	0.4252	0.5342	0.5404	0.5373
5	1.0000	0.4750	0.0000	0.5250	1.0000	0.4878	0.7439
6	0.8387	0.5812	0.1613	0.4188	0.7561	0.5442	0.6501
7	0.3823	1.0000	0.6177	0.0000	0.4474	1.0000	0.7237
8	0.4683	0.6762	0.5317	0.3238	0.4846	0.6069	0.5458
9	0.1316	0.7514	0.8684	0.2486	0.3654	0.6679	0.5167
10	0.7959	0.7648	0.2041	0.2352	0.7102	0.6801	0.6951
11	0.0000	0.0000	1.0000	1.0000	0.3333	0.3333	0.3333
12	0.7896	0.8854	0.2104	0.1146	0.7038	0.8136	0.7587
13	0.1391	0.6584	0.8609	0.3416	0.3674	0.5941	0.4808
14	0.1348	0.4143	0.8652	0.5857	0.3662	0.4605	0.4134
15	0.8724	0.2444	0.1276	0.7556	0.7966	0.3982	0.5974
16	0.5386	0.6165	0.4614	0.3835	0.5201	0.5659	0.5430

Table 4. Response Table for Grey Relational Grade

Factors	Level 1	Level 2	Level 3	Level 4	Rank
pH	0.5288	0.6659	0.576	0.5086	2
Temperature	0.5252	0.5977	0.5602	0.5962	4
Solid Concentration	0.4715	0.6831	0.5156	0.6092	1
C/N	0.5638	0.498	0.6421	0.5754	3

After calculating the S/N ratio for the measured responses, normalizing is done using the **equation no. 1. Table 3** shows the values of normalizing and deviation sequence of the individual S/N ratio using grey relational technique. Next Grey relational coefficient is calculated for individual responses after the normalizing process of data and deviation sequence. In this work, biogas yield and VSRR have to be higher and hence larger-the- better concept is used. By considering the average values of grey relational coefficient corresponding to the input parameter level value, grey relational grade is calculated as shown in **Table 3.**

Observations made from response **Table 4** reveal that the most critical parameter is Solid concentration, which has a higher deviation of average grey relational grade. From response table, optimum conditions are solid concentration of 13.5% of TS, pH 7.4, temperature of 26°C and C/N ratio of 15.3, represented as A2B2C2D3. Main effects plot is drawn for the weighted grey relational grade from the response table, as shown in **figure 3.**

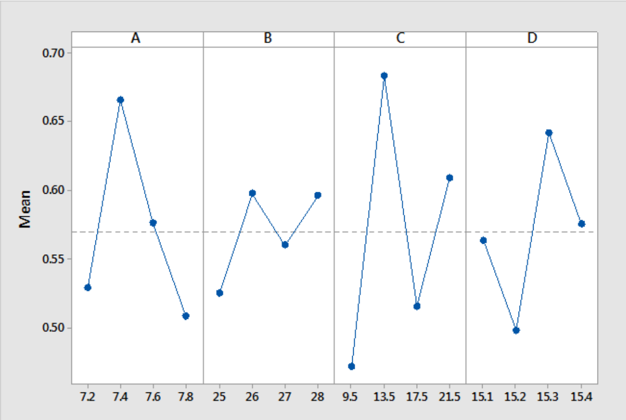

Figure 3. Main effects plot for grey relational grade

The ANOVA analysis in **Table 5.** shows that the Solid Concentration is the most influential factor due to its higher percentage contribution (42.41%) among the process parameters, which is followed by pH 23.08 %, C/N 16.19 % and temperature by 5.59 %. By controlling the solid concentration level inside the digester will enhance the biogas yield.

Table 5. Analysis of variance for grey relational grade

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	%
pH	3	0.0587	0.0195	1.85	0.313	23.08
Temperature	3	0.0142	0.0047	0.45	0.737	5.59
Solid Concentration	3	0.1079	0.0359	3.4	0.171	42.41
C/N	3	0.0418	0.0139	1.32	0.414	16.42
Error	3	0.0317	0.0105			12.48
Total	15	0.2545				100.00

CONCLUSION

This study proposes an approach integrating the Taguchi method and GRA to identify optimal combination of process parameters required to meet multiple quality objectives in biogas production of poultry litter by AD process. By applying Taguchi-GRA technique, the optimized condition obtained for anaerobic digestion of poultry litter is Solid concentration of 13.5% TS, pH of 7.4, temperature of 26℃and C/N ratio of 15.3. ANOVA result shows that Solid concentration is the most significant and influencing input parameter contributing towards the grey relational grade by 42.41%, then followed by pH, temperature and C/N ratio. This study discloses that, biogas yield can be maximized and the process can be controlled by improving the carbon-nitrogen ratio of the substrate and maintaining the digestion process parameters in optimal level.

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