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Optimization of process factors for the efficient generation of biogas from raw vegetable wastes under the direct influence of plastic materials using Taguchi methodology

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ABSTRACT

In this investigation, the combined process efficiency with respect to biogas generation was evaluated by Taguchi robust design using raw vegetable wastes (RVW) and waste plastics (WP) as the key components. The signal-to-noise (S/N) ratio was used to estimate the main effects, interaction effects, and optimal levels of the process factors. Among the various experimental combinations, statistical analysis of the optimized result showed that enhanced biogas production could be achieved with the plastic content (15%), height to diameter (h/D) ratio (30), water content (125 ml), and digestion period (18 week). The Taguchi methodology predicted a maximum biogas (24.83 m^3/ton of RVW) could be generated with those selected process parameters under optimized condition. The experimental data showed that enhanced biogas production (24.16 m^3/ton of RVW) was found with the optimized conditions.

Keywords: Raw vegetable wastes; Waste plastics; Biogas; Taguchi robust design; Hydrolyzed material

1. Introduction

The increasing demand for rapid urbanization and fast socioeconomic development would lead to the higher generation of municipal solid wastes (MSW) [1]. The quantities of waste materials as a whole differ from place to place all over the world. Among all the waste materials in MSW, raw vegetable waste materials (RVW) are biodegradable in nature and one of the major carbonaceous contributors. Waste plastics (WP), another potential health hazardous material of varied sizes, quantities, and qualities are often found at random in MSW. Most of them are nonbiodegradable and impermeable in nature. Therefore, inevitably they constrain the easy down flow of hydrolyzed material (HM) in the waste bed (WB) during the anaerobic biodigestion of MSW where that HM is the combined effect of initial moisture content or water associated with the waste materials and leachate generated *in situ* in the WB. Hence, that instinctive property of impermeability of WP was considered here as the

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primary basis of this study instead of the conventional cost induced mechanical or other artificial leachate recirculation process to run the entire solid waste management system efficiently [2,3].

Presently, the modern municipal waste management system suggests segregating and separating the WP as far as possible prior to landfill operation, which is practically a difficult task. Moreover, the cost of the entire operation is another big question. Again, in the landfill site, the poor, faulty, and inefficient treatment mechanism leads to the groundwater contamination due to percolation of HM and the risk of explosion due to uncontrolled methane generation [4–6].

The overall biochemical reaction for anaerobic digestion as suggested by Cossu et al. [16] may be represented as:

$$\begin{aligned} &C_aH_bO_cN_d + [(4a - b - 2c + 3d)/4]H_2O \\ &\quad \rightarrow [(4a + b - 2c - 3d)/8]CH_4 + [(4a - b + 2c \\ &\qquad + 3d)/8]CO_2 + dNH_3 \end{aligned}$$

The major product of this digestion process is biogas, which can be the better alternative to fossil fuels and reduces the emission of greenhouse gases [7–10]. The solid residue formed in due course of reaction mechanism, may be used as an amendment of soil [11–14].

Since a long back, researchers are trying to develop suitable models in this context considering spatially dependent parameters that cannot be properly characterized due to arbitrariness of the data and the possible complexities of the system. No suitable study was found on the biodegradation of those waste materials in combination with the WP to draw the suitable conclusion. Therefore, an attempt was made in this study to use the nonbiodegradable and impervious plastics in the WB to make an affirmative conclusion in contrast to the conventional nonusage of plastics and external recirculation of HM to the WB [2,15]. The underlying justification showed that the unsystematic presence of WP in the WB would have an augmenting effect on the compactness of the WB during bioconsolidation and *thus* WB behaved as a packed bed. Consequently, this made a number of changes in the field capacity of the WB considering the porous areas [6]. This enhanced the hydrolysis stage of the anaerobic bioprocess on holding the HM for a longer period in the void spaces of the WB and ameliorated the microbial enzymatic activities faster. Those void spaces were formed physically in the WB due to the random presence of WP in it. Hence, that would be a better alternative to the cost involved artificial water or leachate recirculation process which in turn reduced the time and cost of whole operation.

Considering the stoichiometric approach, initially both RVW and H_2O (the initial moisture content) might be considered as limiting reactants [16]. However, due to the random presence of WP in the WB, the HM available *in situ* in the pockets formed physically by the WP could be considered as excess reactant for the anaerobic biochemical reaction mechanisms. This would lead to the higher and efficient generation of biogas by regulating the entire anaerobic biodigestion process [6,17]. Again, by stoichiometry, the changes in the chemical oxygen demand values during the anaerobic fermentation mechanisms are often used to make an account for the methane production [18]. Furthermore, on investigation, height to diameter ratio (h/D) of the WB reactors, water content (WC) and digestion time (DT) were compared and verified along with the plastic materials as important measureable controlling parameters to establish the optimized model using Taguchi methodology.

Taguchi orthogonal array (OA) is one of the factorial-based designs which facilitates the study of a system by a set of independent variables over a specific level [19]. This approach allows statistically and ideally similar information with fewer experiments [20] and facilitates to identify the influence of individual factors, establishing the relationship between factors and operational conditions. Taguchi method recommends the use of the signal-to-noise (S/N) ratio to measure the quality characteristics. Based on the analysis of S/N ratio, the optimal levels of the process factors were determined. Furthermore, analysis of variance (ANOVA) was performed to evaluate the statistically significant process factors. Finally, the experiment (in triplicate) was conducted to verify the optimal process factors obtained through the Taguchi method [21]. Recently, this method has been successfully used to improve many other bioprocess applications [22,23].

In this study, Taguchi's method was used successfully to optimize the process parameters for biogas production. The experiments were designed for four factors at four levels with OA layout of L_{16} (4^4).

2. Materials and methods

2.1. Experimental basis and analysis

In this present study, two types of raw materials were used as feedstock. The first raw material was RVW which was collected from different local vegetable market places. The second one was various categories of WP (nonbiodegradable and impermeable) collected from different open dumping yards in local municipal areas. After collection, both of those raw materials were cut into smaller pieces separately. That was done to maintain the effective surface contact between the RVW and the WP for an efficient bioprocess mechanism in the WB reactors.

The statistical software package, Qualitek-4 software (Nutek Inc., MI, USA), was used here to analyze the experimental design, analysis and the experimental data.

2.2. Taguchi methodology

Taguchi method involves the establishment of different experimental situations through orthogonal arrays (OAs) to reduce the experimental errors for enhancing the efficiency and reproducibility of the experiments. Robust design was considered in this study because it helped to minimize the effect of noise factor in the process of optimization and led to a dynamic or robust experimental design [24]. In this optimization study, four phases were considered using Taguchi methodology. Those were planning (design of experiments), conducting (biogas generation with selected factors and levels), analysis (data analysis and prediction of performance), and validation (validation of the experimental model), respectively. The schematic representation of the planned methodology is shown in Fig. 1. Each phase was separated with distinct objective and connected sequence wise to achieve the overall optimized process.

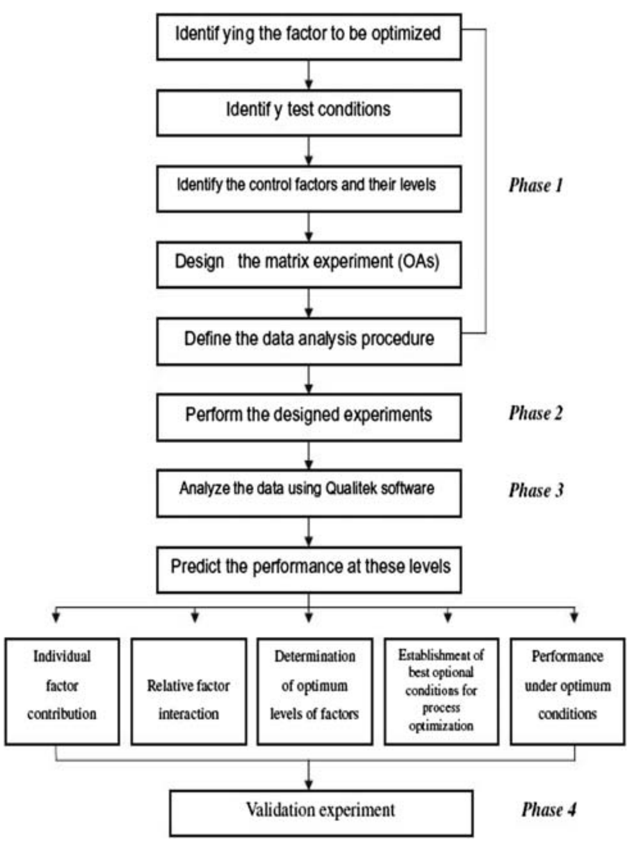

Fig. 1. Schematic representation of the steps involved in the Taguchi DOE methodology.

2.2.1. Design of experiments (Phase 1)

In Phase 1, the first step was to determine the various important factors. The controlling process parameters were observed to have a critical effect on the biogas generation during this lab-scale investigation under strict anaerobic condition. All the variables were considered within the feasible range so that the variation inherent in the process did not mask the factor effect. In this study, plastic content, WC, h/D ratio, and DP (week) were considered as important factors for their efficient contribution to biogas production from RVW. The above mentioned factors were investigated then at four widely spaced levels, as shown in Table 1 decided from previous unreported work. In the next step, matrix was designed with the appropriate OAs for the selected parameters and their levels. Taguchi provided many standard OAs and corresponding linear graphs for this purpose [25]. In the present study, four levels of four factors (Tables 1 and 2) were considered and the size of the experimentation was represented by symbolic array of L-16 (which indicated 16 experimental trials in triplicate).

2.2.2. Biogas generation with selected factors and levels (Phase 2)

At the onset of the experiment, desired numbers of nonmetallic containers of different known dimensions with same volumetric capacities of two liters to each

Table 1
Experimental range of the four numerical variables studied using Taguchi methodology

Serial no.	Factor code	Factor	Level 1	Level 2	Level 3	Level 4
1	**A**	Plastic content (%)	5	10	15	20
2	**B**	h/D ratio	20	25	30	35
3	**C**	Water content (ml)	100	125	150	175
4	**D**	Digestion period (Week)	15	16	17	18

Table 2
L_{16} OA (4^4) of design experiments for four variables with biogas production

Number of experiments	Process parameters				Biogas generation (m^3/ton of RVW) (triplicate experiments)		
	A	**B**	**C**	**D**			
1	1	1	1	1	6.81	7.53	7.17
2	1	2	2	2	9.53	10.54	10.03
3	1	3	3	3	12.26	13.55	12.9
4	1	4	4	4	12.26	13.55	12.9
5	2	1	2	3	15.8	15.05	14.3
6	2	2	1	4	17.92	18.82	17.02
7	2	3	4	1	10.89	11.47	12.04
8	2	4	3	2	14.98	15.77	16.56
9	3	1	3	4	17.7	19.57	18.64
10	3	2	4	3	14.3	15.8	15.05
11	3	3	1	2	14.3	15.8	15.05
12	3	4	2	1	15.77	14.98	16.56
13	4	1	4	2	7.49	7.88	8.28
14	4	2	3	1	7.49	7.88	8.28
15	4	3	2	4	15.77	14.98	16.56
16	4	4	1	3	13.62	12.94	14.3

of them were made ready as WB reactors. They were then filled up with the physically processed and pre-calculated raw materials and sealed accordingly to maintain the strict anaerobic condition. As said earlier, here RVW (fixed amount of 400 g added to each container) considered as the key raw material for this experiment because of its enormous potential carbon source which actually responsible for the effective generation of biogas. However, to establish the catalytic impact of plastics in the WB during anaerobic biodigestion of RVW, WP (5%, 10%, 15%, and 20% to the weight of RVW) and water (100 ml, 125 ml, 150 ml, and 175 ml) were added to the respective WB reactors whose h/D ratio maintained as 20, 25, 30, and 35. The DP considered as per weekly basis of 15, 16, 17, and 18 (Table 1). The leachate samples were collected then separately after stipulated DP from the respective reactors. The said samples were then tested for the estimation of TOC (total organic carbon) content using standard methods and instruments [26] and separately noted. Hence, the corresponding biogas generation was calculated theoretically on the basis of TOC values of those leachate samples by using Ehrig's equation [27]. The Ehrig's equation followed as:

$$Ge = 1.868C(0.014T + 0.28) \tag{1}$$

where Ge = total gas quantity (cubic meter per ton of RVW), C = TOC (kg per ton of RVW), and T = temperature (℃).

2.2.3. Data analysis and prediction of performance (Phase 3)

The experimental data obtained was processed using Qualitek-4 software (Nutek Inc., MI, USA) to evaluate the influence of individual factor, multiple interaction of the selected factors, determination of optimum conditions, and the process performance on biogas production. In the present study, signal-to-noise analysis was employed with bigger is better performance characteristics for all the experimental cases. In the Taguchi method, the term "signal" represents the desirable value (mean) and the term "noise" represents the undesirable value (standard deviation) for the output characteristic [23]. Therefore, the S/N ratio is the ratio of the mean to the standard deviation (SD). Taguchi used the S/N ratio to measure the quality characteristic deviating from the desired value. A loss function [$L(y)$] is developed for the deviation [19] as represented by $L(y) = k \times 1/(y - m)^2$, where k denotes the proportionality constant, m represents the target value, and y is the experimental value obtained for each trial. In case of bigger and better quality characteristics, the loss function can be written as $L(y) = k \times (1/y^2)$ and the expected loss function can be represented by

$$L(y) = k \times 1/(y - m)^2 \tag{2}$$

where $E(1/y^2)$ can be estimated from a sample of "n" as

$$\sum_{i=1}^{n}[1/y_i^2]/n \tag{3}$$

Taguchi used that S/N ratio also as a performance measurement of a dynamic system to evaluate the robustness of the overall process [28]. The performance statistics which measure deviation from the target is called as mean square deviation (MSD). Therefore, the mathematical expression for the S/N ratio for the "bigger is better" case is written as

$$Z = -10\log(\mathrm{MSD}) = -10\log\sum_{i=1}^{n}[1/y_i^2]/n \tag{4}$$

2.2.4. Validation of the experimental model (Phase 4)

In order to validate the methodology, the experiment (in triplicate) was performed further for biogas production using the predicted optimized process conditions. The experimental results were verified and compared with the optimized values.

3. Results and discussion

Present days rapidly increasing energy demand and considering the higher calorific value of the fuels used, the large-scale biogas production is often encountered as an important alternative to the limited sources of fossil fuels. Hence, carbonaceous materials, the essential biodegradable parts of MSW are the principle contributor for the biogas generation which can be managed through systematic landfill management system. This in turn reduces the green house gases also. Here in this research work, an attempt was made to ascertain the above fact by using WP for the availability of HM as an essential excess reactant in the WB instead of additional cost involved mechanically managed water or leachate recirculation. Therefore, in this study to establish the new dimension of use of WP, a systematic and robust optimization strategy was adopted to find out the optimum critical process parameters for enhanced generation of biogas.

3.1. Taguchi methodology

3.1.1. Influence of individual factor

The influence of each factor at the assigned levels on biogas production is represented in Table 2. Results obtained with the designed experimental sets (Table 3) show that the process efficiency is found to be very much dependent on the selected process parameters. Individually plastic content, DP, WC, and h/D ratio are very influential at level 1, level 2, level 3, and level 4, respectively, for the biogas generation. The magnitude of difference between the average effects ($L_2 - L_1$) represents the relative influence of the corresponding factors or interaction for the variability of the results. The Taguchi methodology follows that larger the difference, the stronger is the influence [25]. The present findings explain that among the studied factors, plastic content followed by DP, WC, and h/D ratio shows the stronger influence on the effective generation of biogas (Table 3).

Results show that higher generation of biogas is produced with the subsequent increase of plastic content up to the level 3. However, further raising the plastic content (level 4), biogas production decreases. Such production variation can be happened due to low contact between the RVW and HM [6]. This may be physically explained due to restriction in natural flow movement of HM, caused by the excess plastic materials present in the WB and pretends as path barrier. While in the case of DP, the higher biogas production is found with subsequent increase of it up to the level 4. Such variation is occurred due to the presence of HM for a longer time in the WB resulting in the formation of more leachate and is leading to the

Table 3
Main effects of selected factors

Serial no.	Factor code	Factor	Effect of individual factors in Biogas production (S/N ration)				($L_2 - L_1$)
			Level 1	Level 2	Level 3	Level 4	
1	**A**	Plastic content	20.37	23.42	24.09	20.61	3.05
2	**B**	h/D ratio	20.98	21.62	22.71	23.18	0.64
3	**C**	Water content	22.08	22.85	22.36	21.20	0.77
4	**D**	Digestion period	20.03	21.35	22.98	24.14	1.32

generation of more biogas [6,16]. Results show that higher biogas production is found with subsequent increase of WC (level 2) and further rising of its concentration (levels 3 and 4) decreases the generation of biogas. Considering the hydrolysis stage and stoichiometric factors involved in the anaerobic biochemical reaction mechanisms, this can be explained that the excess WC may dilute the HM [16]. This dilution may increase the pH and partially restricts the solubilization of RVW of higher molecular weight at acidic condition to form the compounds of lower molecular weight, which in turn decelerates the hydrolysis and further stages, respectively. Ultimately the biogas generation will be long-winded [29]. Considering the h/D ratio, it is found that the biogas generation increases subsequently up to the level 3. This shows the dimensional limitations of the reactors considered for the specific anaerobic biodigestion process and can be attributed to fix up the dimensions of a model WB reactor because it directly interfere the bed compression and subsequently anaerobic digestion in a faster mode [30–32].

3.2. *Influence of factors interaction*

The severity index (SI) is evaluated from Taguchi Design of Experiment (DOE) that represents the influence of two individual factors at various levels of interaction (Table 4). In this table, the “columns” represent the locations to which the interacting factors are assigned. The 100% SI indicates 90° angle between the lines (factors), while 0% SI for the parallel lines. Reserved column (RC) explains that it should be reserved if this interaction effect has to be studied while “levels” indicate the level of factors desirable for the optimum conditions.

The highest interaction is observed in between h/D ratio and WC (SI 69.17%) followed by WC and DP (SI 62.48%), plastic content and WC (SI 26.72%), plastic content and h/D ratio (SI 8.45%), h/D ratio and DP (SI 7.65%), and plastic content and DP (SI 0.9%) on the biogas generation, respectively (Table 4). This can be considered from the Table 3 that the plastic content, DP, WC, and h/D ratio are assigned as highest, higher, lower, and lowest impact factors for the efficient generation of biogas. However, it is interesting to note that WC and h/D ratios are the lower and lowest impact factors, respectively, but they have shown the higher SI when considered together. WC is the lower impact factor but has shown the higher SI in combination with DP and plastic content which are higher and highest impact factors, respectively. The h/D is the lowest impact factor but has shown the moderate SI in combination with plastic content and DP which are highest and high impact factors, respectively. In the contrary, lowest SI of 0.9% is found in combination with plastic content (highest impact factor) and DP (high impact factor).

Therefore, it is evident from the results that the yield is quite independent of the individual influence of those factors but depends on the interaction of the factors involved.

3.3. *ANOVA*

Analysis of variance (ANOVA) is used here to analyze the experimental data and to determine the variation of results due to each factor. Based on F (Fisher’s test) ratio, it is observed that all the factors and interactions are statistically significant within 95% confidence level. ANOVA with the percentage of contribution of each factor with interactions are shown in Table 5. Result shows that plastic content contributed the maximum impact (42.49%) followed by DP (37.98%), h/D ratio (11.25%), and WC (5.02%), respectively, for the enhanced generation of biogas during experimentation.

Fig. 2 shows the variation of biogas generation at the chosen levels of each significant factor. Individually, each significant factor influences the production of biogas at certain level. However, in selective combination, the levels of significant factors are different for

Table 4
Estimated interaction of severity index for two factors

SN	Biogas production Factors	Columns	SII (100%)	RC	Levels
1	h/D ratio × Water content	2 × 3	69.17	1	[1,3]
2	Water content × Digestion period	3 × 4	62.48	7	[3,4]
3	Plastic content × Water content	1 × 3	26.72	2	[3,3]
4	Plastic content × h/D ratio	1 × 2	8.45	3	[3,1]
5	h/D ratio × Digestion period	2 × 4	7.65	6	[1,4]
6	Plastic content × Digestion period	1 × 4	0.9	5	[3,4]

Table 5
Analysis of variance (ANOVA) for biogas generation

Factor	Biogas production					
	DOF	SS	Variance	*F*-ratio	Pure sum	Percentage of contribution
Plastic content	3	43.77	14.59	66.16	43.11	42.49
h/D	3	12.07	4.02	18.25	11.49	11.25
Water content	3	5.75	1.92	8.70	5.09	5.02
Digestion period (week)	3	39.2	13.07	59.25	38.54	37.98
Other/error	3	0.66	0.22			3.26
Total	15	101.46				100%

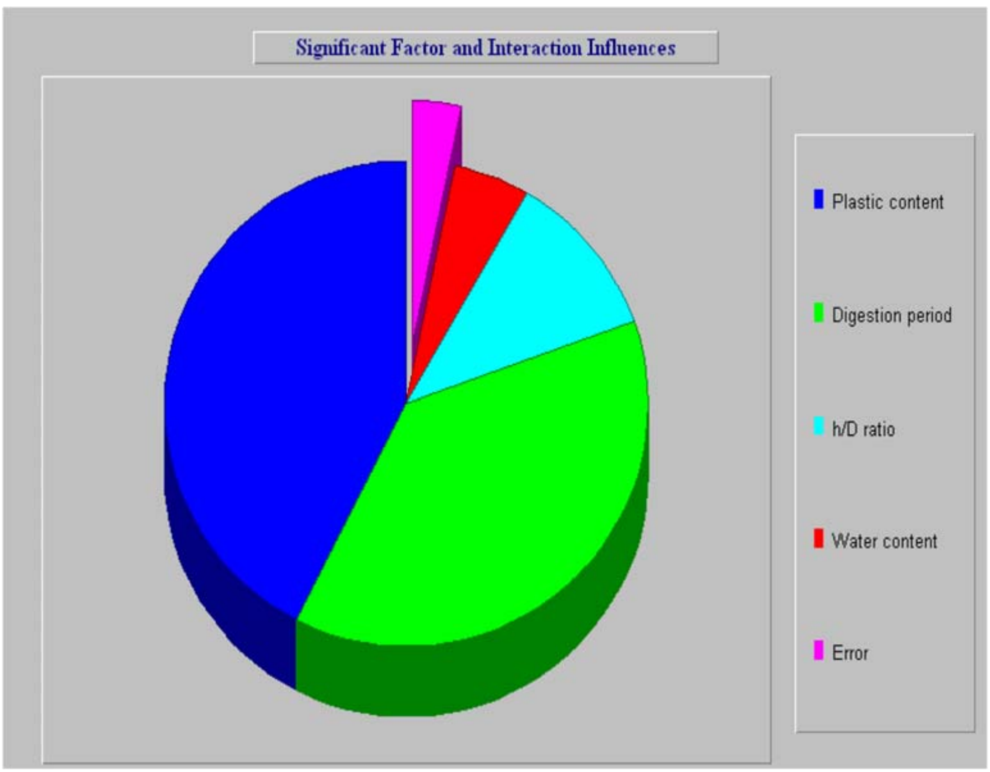

Fig. 2. Relative influence of factors and interaction for biogas production.

maximum generation of biogas, which may be reasoned due to the interactive effect of the considering factors. Fig. 3 illustrates the contribution of those selected factors at optimum performance level for the efficient generation of biogas.

3.4. Optimum process parameters

Optimum consideration of those significant factors and their performance in terms of contribution for achieving higher biogas yield is shown in Table 6. It can be seen from the table that DP shows the maximum impact followed by plastic content, h/D ratio, and WC on the generation of biogas. Taguchi DOE suggests that the higher levels of biogas yield can be achieved with plastic content (15%), h/D ratio (30), WC (125 ml), and DP (18 weeks). The expected biogas production at optimized condition by S/N ratio is estimated as 27.90 (total contribution from all the factors is 5.78 with grand average performance of 22.12).

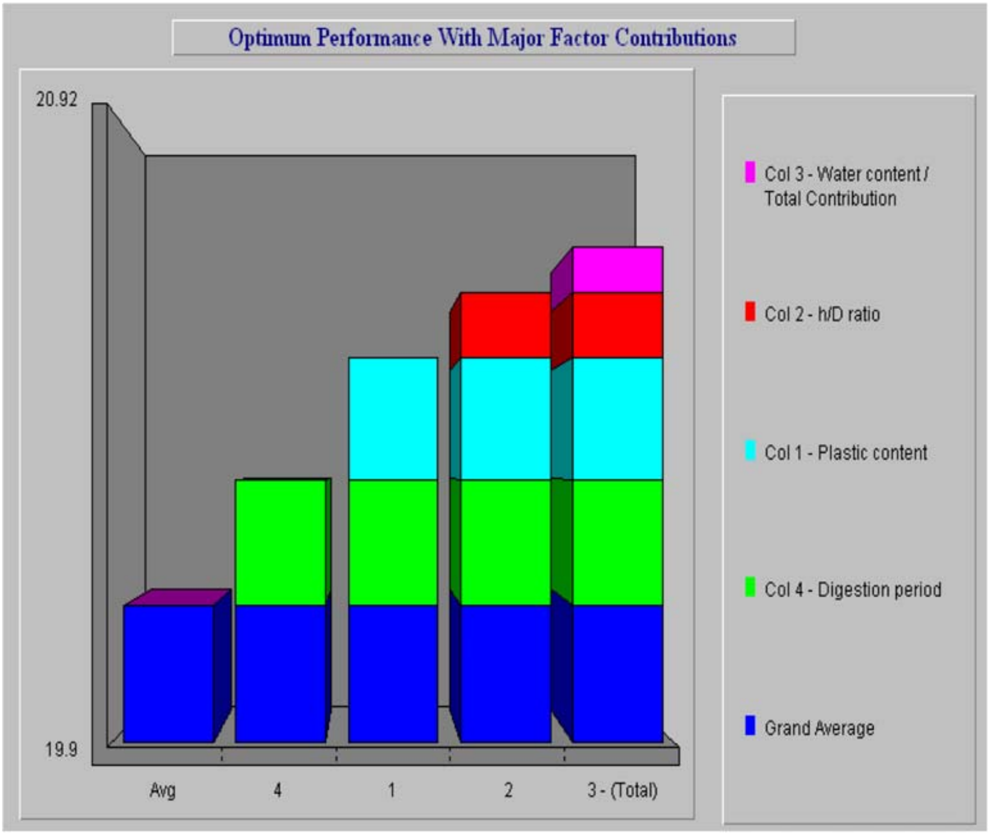

Fig. 3. Optimum performance with major factor contributions for biogas production.

Table 6
Optimum conditions for biogas production

Factor code	Factor	Values	Level	Contribution for biogas production (S/N ratio)
A	Plastic content	15	3	1.97
B	h/D ratio	30	4	1.06
C	Water content	125	2	0.73
D	Digestion period	18	4	2.02
	Total contributions from all factors			5.78
	Current grand average performance			22.12
	Expected result at optimum conditions			27.90

The estimated biogas generation by the S/N ratio is calculated as 24.83 m^3/ton of RVW with MSD of 0.001623 [by Eq. (4)].

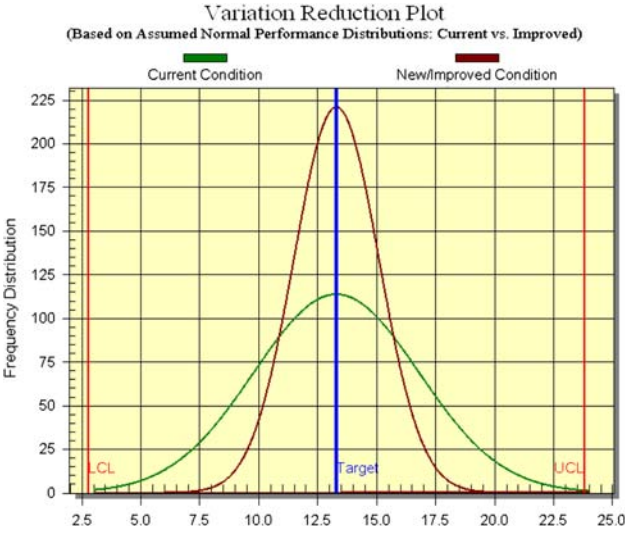

Fig. 4. Performance distribution of current and improved conditions for biogas production.

3.5. Validation experiments

Fig. 4 shows the frequency distribution of current condition along with the improved condition. It is evident from Fig. 4 that the biogas yield can be increased from 12.77 to 24.83 m^3/ton of RVW. Therefore, the overall 94.45% enhancement in the biogas yield can be achieved on considering the optimized process conditions. Further to validate the proposed experimental methodology, corresponding experiment was performed by the obtained optimized process parameters. The experimental data showed that the enhanced biogas generation (24.16 m^3/ton of RVW) was found with the optimized conditions.

4. Conclusion

Taguchi methodology was successfully applied to optimize the process factors for enhanced biogas production using RVW as principle raw material under the positive influence of plastic content in addition with WC and was experimentally verified in consideration with suitable h/D ratio of the WB reactor. The main effects, interaction effects, and the optimal levels of the process factors were determined using S/N ratio.

Therefore, it can be concluded from the study that the enhanced biogas generation (24.16 m^3/ton of RVW) is much closer to the predicted maximum generation of biogas (24.83 m^3/ton of RVW) using Taguchi methodology under the optimized conditions and this supports the study.

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