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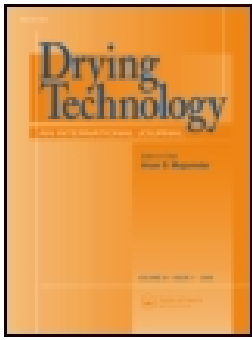
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Effect of waste matrix for the optimization of moisture content and calorific value of biodried material using Taguchi DOE

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ABSTRACT

In this study, Taguchi approach was used to determine the influence of waste composition for the optimization of moisture content (MC) and calorific value (CV) of food waste via bio-drying process. The objective was to reduce MC and increase CV of the bio-dried material. The effect of three different levels of four factors including food (FW), paper (Pa), plastic (Pl) waste, and bulking agent (BA) were studied and optimized. The moisture content of the bio-dried material varied between 8.59 and 50.93%, whereas that of the calorific value was 11–25 MJ/kg. The results revealed optimum configurations for MC and CV as FW₁Pa₃Pl₃BA₃ and FW₁Pa₁Pl₃BA₁, respectively. Regression analysis revealed MC as a positive function of FW and BA with plastic positively correlated with calorific value. ANOVA analysis indicated that FW had more prominent effect on both MC and CV. The predicted and measured values were very close to each other. Additionally, the results realized in the confirmatory experiments at optimized conditions of CV was found to be higher than the test runs of Taguchi design, suggesting that Taguchi method was very successful in the optimization of bio-drying factors for MC and CV.

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Moisture content; calorific value; Taguchi design; optimization; food waste

Introduction

With the rapid urbanization and fast socioeconomic development across the globe, municipal solid waste (MSW) generation is expected to dramatically increase.^[1] A significant portion of this MSW consists of food waste, which is the biodegradable portion of MSW, with more than 1.3 billion tonnes of food waste generated annually.^[2,3] However, the disposal of this waste in landfill has dire consequences on the environment including the generation of methane, which can pose a threat or contribute to the greenhouse.^[4–6]

From economic and environmental standpoint, it is imperative to control these food wastes and be able to convert them to valuable products. In recent years, the management of waste has shifted from disposal to beneficial utilization due to the introduction of new regulations coupled with high cost of landfill. Consequently, composting has been identified as an alternative method for transforming the organic fraction of waste into a potentially safe, stable, and sanitary product that can be used as a soil amendment or an organic fertilizer.^[7] Nevertheless, the high process cost, long residence time (30–50 days), and low

quality of final compost have hindered wider application of composting as an appropriate technology for waste treatment.^[8]

According to directive 2008/98/EC, waste incineration can be categorized either as a disposal or energy recovery technology depending on the energy efficiency of the incineration plant.^[9] Hence, the operation and design of the aforementioned process highly requires the knowledge of its thermal properties with energy content being perhaps the most important of the input material. The standard measure of the energy content of any fuel is its heating value (HV) also called calorific value (CV) or heat of combustion.^[10,11] However, due to the high moisture content (MC) of food waste in addition to its limited lower calorific value (3–6.7 MJ/kg), direct food waste incineration is not cost-efficient.^[12] Thus, to achieve efficient incineration of waste with high moisture content, it is imperative to reduce the moisture content of the waste subsequent to incineration.

Bio-drying, as a waste to energy conversion technology, aims at reducing moisture content of waste while maintaining the calorific value of the processed waste.^[8,13,14] Even though this concept is similar to

composting, bio-drying tends to pretreat waste at the lowest possible residence time to produce a high quality bio-dried material. This is accomplished by using the heat generated from the microbial degradation of the waste matrix, in addition to forced aeration.

In recent years, research on bio-drying has focussed on the application of this technology for pre-treating garbage residues and sewage sludge^[15,16] and pulp and paper^[14,17] and MSW,^[18,19] with 50–70% as the optimal initial moisture content range for bio-drying process.^[16,19] It is obvious that bio-drying of food waste has not received much attention by researchers due to its high moisture content and low biomass porosity. The moisture content directly affects the calorific value of a material i.e., as moisture increases, the calorific value of a material decreases. Appropriate moisture content for efficient bio-drying process to achieve higher calorific value is also related to the waste composition and proportion of selected materials. Conventional approach of varying one parameter and keeping remaining parameters constant is often considered an expensive and arduous task. Additionally, conventional modeling approach lacks the ability to study the interactive effects between various process variables on the process output. However, with the advent of new statistical experimental designs described as design of experiments (DOEs), process optimization has become an easy, cheaper, and faster option by making fewer possible experiments.

Among the DOE methods, Taguchi method has become popular due to its systematic, simple, and efficient approach for the optimization of process parameters.^[20] One distinctive feature of the Taguchi approach is its ability to study the main effects of each factor and to model some of the important interactions by one primary experiment.^[21] Several studies have been conducted in optimizing drying process of different waste materials using Taguchi technique. Musabbikhah et al.^[22] reported the application of Taguchi method for optimizing temperature and time for drying and carbonization of coconut shell to increase its calorific value. In another study, Salgado and Neto da Silva^[23] used Taguchi technique in the modeling of paper mill sewage sludge drying. All references cited in literature on bio-drying concern on the production of a bio-dried material with specific emphasis on the effect of bulking agent on bio-drying process.^[16,24–26] Yang et al.^[27] recently studied a review of modeling of bio-drying process and concluded that the modeling of the process ensures energy balance and consequently predict the performance of the process. The application of Taguchi's

method for calorific value optimization by bio-drying process has not been reported in literature till date. Additionally, the contribution of each process variable in achieving high calorific value has not received much attention by researchers.

In the present study, the effect of different proportions of waste materials Pa (Paper), Pl (Plastic), and BA (Bulking agent) ratios on bio-drying of FW (food waste) with the aim of achieving optimum calorific value and moisture content was investigated. The result of the present work in conjunction with previous work of Mohammed et al.^[28] would provide a much better understanding for optimized parameters of bio-drying process. Each of the four independent process parameters had three different possible levels. With regards to the determination of optimal material combinations for maximum and minimum calorific value and moisture content, Taguchi's signal-to-noise ratio was employed. The percentage contribution of each process variable towards a high calorific value was also determined using analysis of variance (ANOVA) statistical method.

Materials and methods

Raw materials

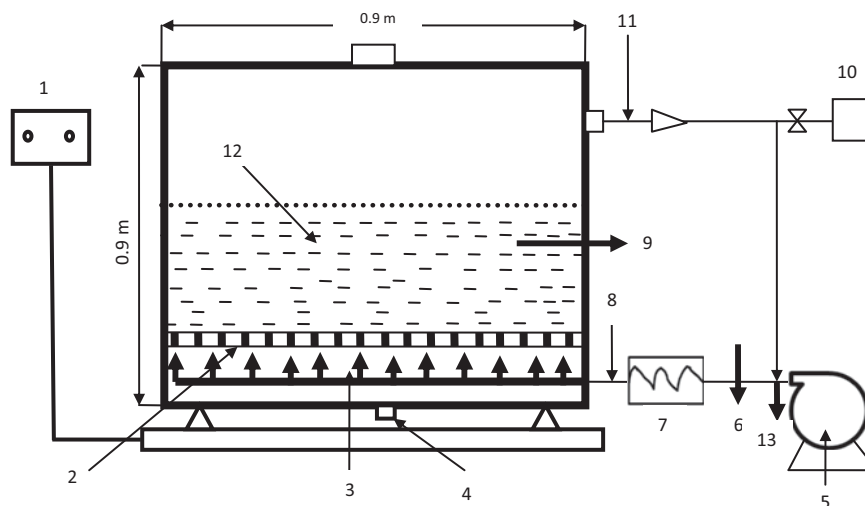
Four different kinds of raw materials, i.e., food, paper, plastic waste, and bulking agent as pruning waste (yard waste or residual waste produced after pruning trees or plants) were used for the experimentation. The FW (*Lactuca sativa*) collected from a canteen of University of Kocaeli was transferred to laboratory at the same day to keep its freshness. The FW was the main waste component to be bio-dried and this was crushed into $15 \times 35 \text{ mm}^2$ particles using a food grinder. However, due to the high MC of FW, and the high contribution of paper (sorted office papers) and plastic (low density polyethylene (LDPE)) as component of MSW, these materials were shredded into different particles; Pa ($2 \times 14 \text{ mm}^2$), Pl ($5 \times 10 \text{ mm}^2$), and BA of 15 mm in diameter, and added in different proportions to initially reduce the moisture component of the FW subsequent to bio-drying. The physiochemical properties of the raw materials are presented in Table 1.

Experimental set-up and procedure

The bio-drying experiments were performed in an adiabatic reactor of 0.8 m^3 made from a stainless steel with a leachate collection system at the bottom (Figure 1). The detail description of the bio-reactor can be found in Appendix 1. A constant and uninterrupted air-flow rate ($15 \text{ m}^3 \text{ h}^{-1}$) was used in all the

Table 1. Characteristics of the raw materials (sn =5).

Parameter	Food waste	Paper	Plastic	BA
Moisture content	91.48 ± 0.58	5.40 ± 0.16	0.94 ± 0.05	8.43 ± 0.33
Volatile solids (%)	98.51 ± 0.22	78.94 ± 0.20	99.57 ± 0.25	90.62 ± 0.38
Bulk density (kg/m ³)	464.18 ± 5.36	100.46 ± 1.01	346.50 ± 3.77	204.14 ± 2.02
CV (MJ/kg)	0.11	12.51	44.65	16.01
Water holding capacity (%)	–	43.04	35.77	68.19


Figure 1. Schematic diagram of the bio-reactor for bio-drying.

trials using a whirlpool pump connected to the bottom of the column while an air-flow meter was used to measure the air flow rate. The period of bio-drying was 7 days for each experimental run with moisture content and calorific value analyzed after the process.

Analytical procedure

The MC of the materials was gravimetrically analyzed following CEN/TS 15414-2 standard (105 °C) using moisture analyzer (Precisa, XM 50), whereas the heat value of the bio-dried material was determined using IKA C-7000 model calorimeter in dry basis (IKA Laboratory Equipment, Werke Staufen, Germany), in accordance with EN 15400 standard. Subsequently, the CV in wet basis was calculated with respect to moisture content as follows:

$$CV_w = CV_d \times (1 - MC) \quad (1)$$

where CW_w = calorific value in wet basis (MJ/kg); CV_d = calorific value in dry basis (MJ/kg); MC = moisture content of wet sample (%). It is worth mentioning that, due to the heterogeneous nature of the waste, the weighted average method was employed in determining the initial MC of the mixed waste, since it was impossible to get a typical sample from the heterogenous mixture of the waste, a similar procedure employed by Shuqing et al.^[29] The volatile

solids (VS) content was analyzed by heating the sample at 600 °C for 5 h in a muffle furnace in accordance with EN 15402. Bulk density defined as the weight per unit volume of material was measured according to CEN/TS 15401. To determine which of the materials were efficient for bio-drying process, the water absorption capacity (WAC), also known as water holding capacity (WHC) of the raw material was determined using a method described by Adhikari et al.^[30] and Malińska and Zabochnicka-Swiatek.^[31] About 3 g of the sample was soaked in distilled water for 24 h and the wet sample was then dried at 105 °C for 24 h after the gravitational water was drained off under cover. The total water absorbed was the difference between the weight of the soaked sample and the weight of the dried sample. The WAC (%) was computed as:

$$WAC(\%) = \left(\frac{W_{SD} - W_D}{W_D} \right) \times 100 \quad (2)$$

where W_{SD} = weight of the soaked and drained sample (g) and W_D = weight of dried sample (g).

Design of experiment using Taguchi methodology

The Taguchi method is a statistical method that has been generally adopted for optimization of process variables.^[32] This technique has found wide usage among researchers due to its significance in

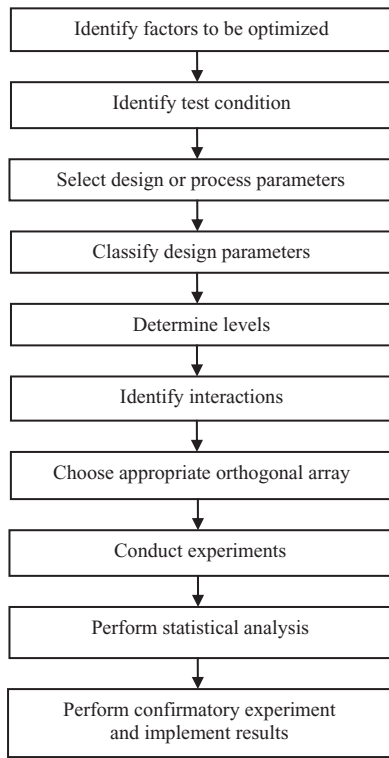


Figure 2. Schematic diagram of the steps involved in the Taguchi DOE methodology designed for optimization.

minimizing overall testing time and cost. It is important in investigating the effects of multiple factors on performance as well as to study the influence of individual factors to determine which factor has more influence or less. The Taguchi DOE utilizes orthogonal arrays (OA) from design of experimental theory to organize the factors affecting the processes with varied levels of factors. Figure 2 represents various phases of Taguchi (DOE) methodology.^[33] In the present experimental investigation, four controllable factors were considered with each factor at three levels (Table 2). Therefore, an L_9 (3^4) OA was chosen. The selected controllable factors were FW, Pa, Pl and BA. The response variables investigated in this study were MC and CV. These factors and their levels were selected based on our preliminary experiments on green waste for bio-dried material production.^[28]

The Taguchi method employs the signal-to-noise (S/N) ratio, to measure the performance of the process response. Based on the analysis of S/N ratio, the optimal levels of the process factors were determined. S/N ratio depends on the criterion for the quality characteristics to be optimized. The characteristic of the S/N ratio is categorized into three criteria: (1) larger-the better (LB), (2) smaller-the-better (SB), and (3) nominal-the best (NB). The LB function aims to maximize the response from a system, while the SB

Table 2. Levels of variables used in the experimental design.

Factor	Description	Unit	Level 1(L1)	Level 2 (L2)	Level 3 (L3)
FW	Food waste	kg	15	25	35
Pa	Paper	kg	2	6	8
Pl	Plastic	kg	3	8	10
BA	Bulking agent	kg	0	3	6

function aims to minimize it. Nominal-the-best targets a nominal value and aims to minimize the variability around it. However, since the present study intends to maximize the removal of moisture content and optimize the calorific value, the LB and SB were selected to obtain the performance characteristics for MC and CV, respectively, using Equations (3) and (4), respectively.

Larger the better (LB):

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{Y_i^2} \right) \quad (3)$$

Smaller the better (SB):

$$S/N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n Y_i^2 \right) \quad (4)$$

where “ n ” is the number of samples for performance response corresponding to the number of design parameter combinations, Y_i is the signal measured in each experiment averaged over n repetitions. The variability characteristic is inversely proportional to the S/N, thus implying that a larger S/N corresponds to a better performance.^[34] Accordingly, the ANOVA statistical approach was employed to statistically study and explore the effects of each factor, in this case, FW, Pa, Pl, and BA on the response variables and to elucidate which factors significantly affect the observed values.

Results and discussion

Effect of waste composition on MC and CV

The decrease in moisture content resulting in an increase in calorific value is an established fact.^[26,35] Figures 3 and 4 show the MC reduction, and percentage changes in MC and CV decrease/increase for each of the experimental runs. Since the CV obtained from the calorimeter was in dry basis, the CV in wet basis was determined according to Equation (1). It is clear in the above figures that, even though R3 had the highest percentage increase in MC, it recorded the lowest percentage increase in CV. This was attributed to the composition of the waste which consisted the lowest amount of FW (highest initial MC) and highest

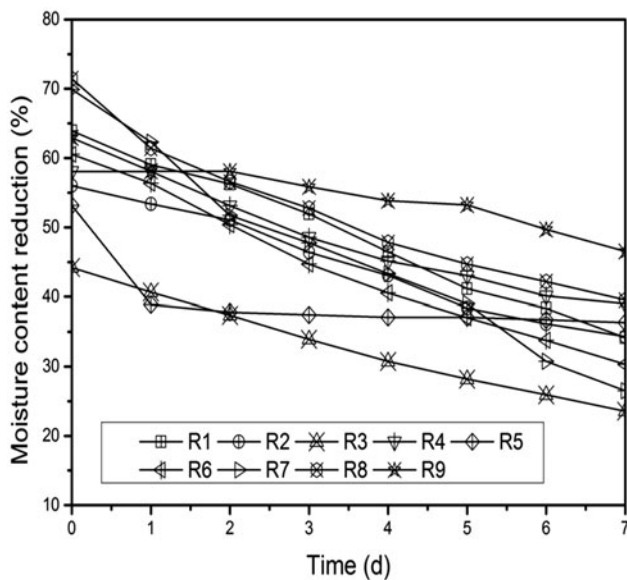


Figure 3. Moisture content reduction with time during bio-drying process.

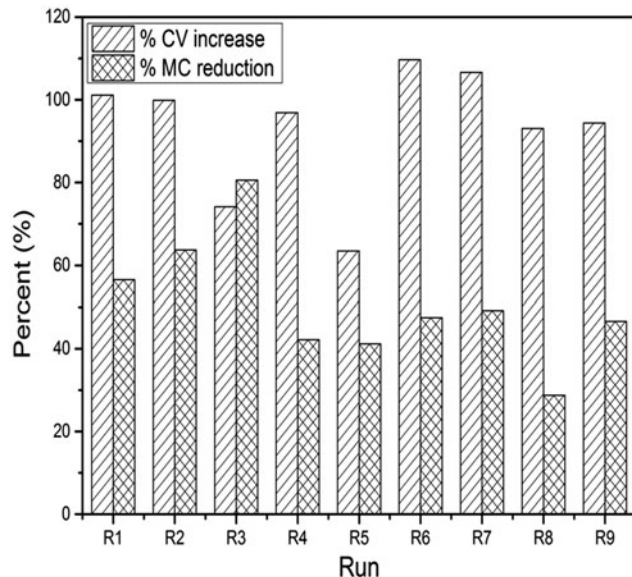


Figure 4. MC reduction and CV increase.

amount of Pa, Pl, and BA. This result suggests that the amount of FW had a critical role in the CV of the bio-dried material due to its high initial MC. Additionally, the low initial MC ensured efficient bio-drying by allowing air to be transported through the waste matrix during the process, thus high MC reduction. On the contrary, R8 had the lowest decrease in MC which could be attributed to the absence of BA, which has the ultimate aim of ensuring initial moisture reduction and creating porous and homogeneous structure to enhance bio-drying process. This implies that BA is an important factor in ensuring efficient bio-drying process as corroborated by other researchers.^[16,24]

Table 3. Experimental layout of L9 and average experimental results of MC and CV with their S/N ratios.

Run	FW	Pa	Pl	BA	MC (%)	S/N	CV (MJ/kg)	S/N
1	1	1	1	1	27.77	-28.87	23.34	27.32
2	1	2	2	2	20.31	-26.15	21.24	26.58
3	1	3	3	3	8.59	-18.68	24.32	27.74
4	2	1	2	3	33.57	-30.52	20.88	26.42
5	2	2	3	1	31.26	-29.90	24.35	27.70
6	2	3	1	2	31.81	-30.05	18.56	25.32
7	3	1	3	2	35.53	-31.01	19.73	25.94
8	3	2	1	3	50.93	-34.14	11.74	21.32
9	3	3	2	1	33.62	-30.53	20.26	26.12

Analysis of optimum conditions

Optimum conditions by Taguchi analysis

The optimization of the response variables were considered from S/N ratio in each level of parameters (Table 3). Figure 5(a,b) depicts the S/N ratio of each individual factor for the response variables. It is seen in Figure 5(a) that the MC increases with an increase in the amount of FW added, as expected. This is due to the low porosity of FW, impeding the easy transport of oxygen within the waste matrix during bio-drying process. As a result, the air spaces within the waste matrix were filled with water instead of air, discouraging effective aeration and biological energy generation during bio-drying.^[16,36] This result suggests an increase in FW in the waste matrix which contains MC of 91% tends to increase the MC of the entire waste matrix, i.e., the higher the amount of FW relative to the other waste materials, the higher the MC of the waste matrix. For factor Pa, the minimum MC value was achieved at L1 (2 kg) and increased from -30.06 to -26.39, this was due to the fact that paper have lower water absorption capacity, thus limiting its ability to absorb leachate during bio-drying. It should also be noted that, it takes a longer time for paper to release the water that is absorbed which is disadvantageous for bio-drying process.^[37,38]

Furthermore, the MC tends to decrease with an increase in plastic waste content (Pl), even though it had no significant impact on the bio-drying process. Similarly, the MC decreased with decrease in the amount of BA, this was due to the reason that the increase in BA tends to adjust the MC of the waste matrix by providing structural support and high porosity, thereby aiding in aeration through the waste matrix. These findings are consistent with those reported by Iqbal et al.^[39] The difference between the maximum (Max) and minimum (Min) value of each factor (Max-Min) indicated the relative influence of each factor on the response i.e., MC and CV. The larger the difference, the stronger the influence. Accordingly, it is evident that FW showed the

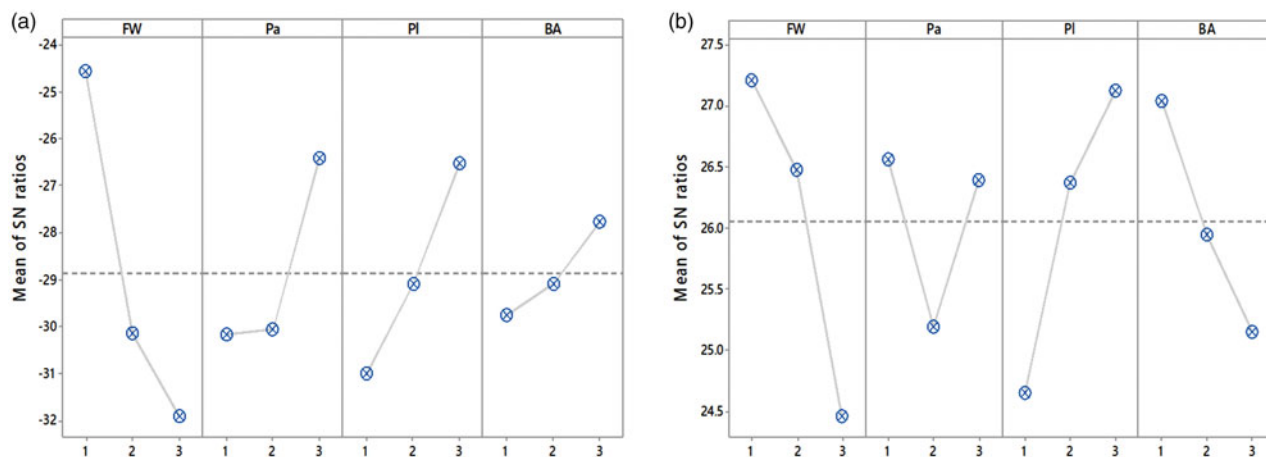


Figure 5. Effect of process parameters on S/N ratio for (a) MC and (b) CV.

Table 4. S/N ratios response table for MC (SB) and CV (LB).

Levels	MC				CV			
	FW	Pa	PI	BA	FW	Pa	PI	BA
1	-24.55	-30.14	-30.99	-29.74	27.21	26.56	24.65	27.05
2	-30.14	-30.06	-29.09	-29.09	26.48	25.20	26.37	25.95
3	-31.90	-26.39	-26.51	-27.76	24.86	26.39	27.13	25.16
Max-Min	7.34	3.75	4.47	1.98	2.75	1.36	2.47	1.89

Bold values show the optimal values

strongest influence (7.35) among the factors studied followed by PI, Pa, and BA (Table 4).

The best level for each control factor was found according to the S/N ratio in the levels of that control factor. Based on this, the levels and S/N ratios for the factors with the best MC was specified as FW (Level 1, S/N = -24.55), Pa (Level 3, S/N = -26.39), PI (Level 3, S/N = -26.51), and BA (Level 3, S/N = -27.76). In other words, an optimum MC was obtained with FW₁ (15 kg), Pa₃ (8 kg), PI₃ (10 kg), and BA₃ (6 kg) according to the “smaller the better”. The highest value of BA, plastic waste, and paper waste content appeared to be the best choice to obtain the low value of MC, while the lowest of FW showed the optimal choice. Interestingly, the optimized conditions obtained were similar to the experimental run with the highest S/N ratio, i.e., R3, the highest MC reduction. The results suggest that the optimization of each factor of the independent factors is a prerequisite for higher MC reduction.

The effect of each factor on CV is presented in Figure 5(b). According to literature, the moisture content has a direct influence on calorific value of a material during combustion process.^[26,28,35] In the present study, the experimental results illustrated in Figure 5(b) shows that CV production levels were found to be very much dependent on the independent variables with higher CV production 27.05, 27.21, and 26.56 observed up to Level 1 of BA, FW, and Pa, respectively, and above these levels CV decreased. An

increase in the amount of FW from 15 kg to 35 kg resulted in a decrease in CV of the waste matrix. This may be attributed to the high moisture content of FW which has a direct influence on bio-drying process as well as the energy content of the bio-dried material. This juxtaposes the fact that optimum MC for bio-drying represents a trade-off between the moisture requirements of the microbes and their simultaneous need for adequate oxygen transport through the matrix.^[40] It is also evident from Figure 5(b) that an increase in the amount of Pa resulted in a decrease in CV of the waste matrix. This could be attributed to its low thermal properties as shown in Table 1. The S/N ratio for BA decreased with an increasing amount of BA in the waste matrix. As indicated earlier, the primary function of BA is to provide structural support for bio-drying without necessarily increasing CV, even though the reduction in MC would subsequently result in high CV. The importance of BA on bio-drying process has recently been highlighted by a number of studies.^[16,24–26] Generally, the increase in calorific value of a material primarily depends on MC and its thermal properties. This evidence is highlighted in factor PI as CV increases with the amount of PI from 3 kg to 10 kg (Table 4). Consequently, it can be inferred that PI showed the second strongest influence (2.47) compared to the other factors followed by BA according to the difference between the maximum and minimum values of each factor (Max-Min).

Similarly, the optimum levels of control factors for maximum CV condition are as follows: FW (Level 1, S/N = 27.21), Pa (Level 1, S/N = 26.56), PI (Level 3, S/N = 27.13), and BA (Level 1, S/N = 27.05). That is, an optimum CV was obtained with FW₁ (15 kg), Pa₁ (2 kg), PI₃ (10 kg), and BA₁ (0 kg) according to the “larger the better”. Pa was identified as the least contributing factor to improving CV. Again, this was due to its lower water

holding capacity and longer water loss rate.^[37] However, the highest PI value appeared to be the best choice to obtain the highest value of CV among the other factors, as expected; while the lowest of BA, FW, and Pa showed the optimal choices.

It should be noted that Figure 5(a,b) shows the effect of controllable factors on S/N ratio measured independently, i.e. without considering the interactions between these factors. However, to better understand the interaction between two factors, the interaction plots give a better insight into the overall process analysis. A factor may interact with any or all of the other factors creating the possibility for the presence of a large number of interactions. The interaction plots for MC and CV are presented in Figure 6(a,b), respectively. In the case of MC, interaction effect was observed between Pa and PI, Pa and BA, and PI and BA. However, FW showed no interaction among the factors under study for MC. With regards to CV,

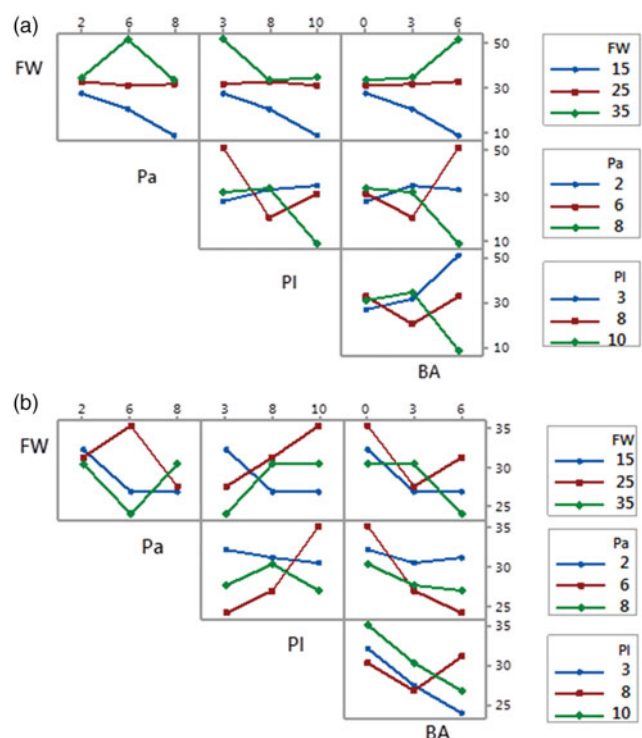


Figure 6. Interaction plots showing the interaction among control factors on (a) MC and (b) CV.

interaction effect was observed between FW and Pa, FW and BA, Pa and BA, and PI and BA. The interaction between PI and BA indicates that the relation between BA and CV depends on PI.

ANOVA results

In order to evaluate the relative importance of each individual factor more systematically, an ANOVA was employed. The main objective of ANOVA is to extract from the results how much variations each factor causes relative to the total variation observed in the result. In this study, ANOVA analysis was performed with a 95% (0.95) confidence level and 5% (0.05) significance level. From the results of ANOVA in Table 5, it was observed that all factors and interactions considered in the experimental design were statistically significant at 95% confidence limit, indicating that nearly all the variability of experimental data can be explained in terms of significant effects. Statistical analyses of MC revealed FW among the selected factors contributed 65% of the total effect. This implies that, factor FW was the most effective one on MC. As seen in Table 5, it can be concluded that second, third, and fourth effective factors on MC reduction were PI, Pa, and BA, respectively, with BA (0.52%) as the least impact on MC.

Similarly, with regards to CV, FW was the most effective factor on CV with a contribution of 43% of the total effect (Table 5). Pa showed the least impact at the individual level on the overall production of higher CV under the selected factors. These discrepancies observed herein could be attributed to the heterogeneous nature of the samples and the wide variation in the input levels of the factors as well as their various thermal properties. The optimal level of control factors for MC and CV is $FW_{15}^a, Pa_3^c, PI_3^b, BA_3^d$ and $FW_{15}^a, Pa_1^d, PI_3^b, BA_1^c$, respectively, with the superscripts indicating the sequence of effective factors. The percent of error was considerably low at 0.01% and 0.07% for MC and CV, respectively. The present study further suggests that a minor variation in the food waste may lead to dramatic change in MC which

Table 5. Results of the analysis of variance—MC and CV.

Variance	MC				CV			
	SS	MS	<i>p</i> value	Contribution (%)	SS	MS	<i>p</i> value	Contribution (%)
FW	1371.47	685.73	1.3×10^{-3}	65.21	104.09	52.05	1.5×10^{-3}	43.09
Pa	306.54	153.27	3.2×10^{-4}	14.58	17.91	8.95	4.4×10^{-3}	7.41
PI	413.92	206.96	5.1×10^{-3}	19.68	77.32	38.66	2.7×10^{-4}	32.01
BA	10.99	5.497	2.3×10^{-3}	0.52	42.09	21.05	7.0×10^{-3}	17.42
Error	0.23	0.026		0.01	0.17	0.019		0.07
Total	2103.15				241.58			

S—0.16; R^2 —99.98%; R^2 (adj)—99.96% S—0.14; R^2 —99.93%; R^2 (adj)—99.72%.

could subsequently affect the energy value of the bio-dried material.

Regression analysis of moisture content and calorific value

Regression analyses are used for modeling and establishing correlation between dependent variable and one or more independent variables. In this study, the dependent variables included FW, Pa, Pl, and BA, whereas the experimental MC and CV were considered as independent variables in the empirical model development using regression analysis. The modeled equations obtained by linear regression analysis of MC and CV are given in Equations (5) and (6).

$$MC_p = 20.74 + 1.058FW - 1.042Pa - 1.624Pl + 0.032BA$$

$$R - Sq = 89.06\%R - Sq(adj) = 87.49\%$$

(5)

$$CV_p = 25.24 - 0.2875FW - 0.125Pa + 0.699Pl - 0.6BA$$

$$R - Sq = 88.94\%R - Sq(adj) = 87.36\%$$

(6)

where MC_p and CV_p indicate the predicted equations for MC and CV in % and MJ/kg, respectively. Figure 7(a,b) depicts the correlation between the experimental results (actual) and the predicted model in this study. It is evidence from the predicted models that the MC_p is a positive function of FW and BA, implying that higher FW corresponds to higher MC. From bio-drying perspectives, the essence of BA is to adjust the initial moisture content and facilitates air movement through the waste matrix. On the contrary, the plastic waste is positively correlated with the predicted calorific value CV_p , as expected. Additionally, compared with the other independent components of the predicted model, Pl was the highest contributor. This clearly indicates that calorific value is directly related to the amount of plastic waste content in a waste mix (Table 3). It should be emphasized that, even though plastic waste has high CV, its amount in the waste mix should be controlled during incineration due to air pollution caused by the noxious fumes released into the atmospheres. The correlation coefficients of the modeled equations (Equations 5 and 6) for MC and CV are 0.89 and 0.88. This shows that the regression between the predicted model outputs and its corresponding input variables proved to be significant. Consequently, it can be concluded that the developed model can be used to predict the CV and MC of bio-dried material. However, it should be pointed that the substrate used should consist of similar

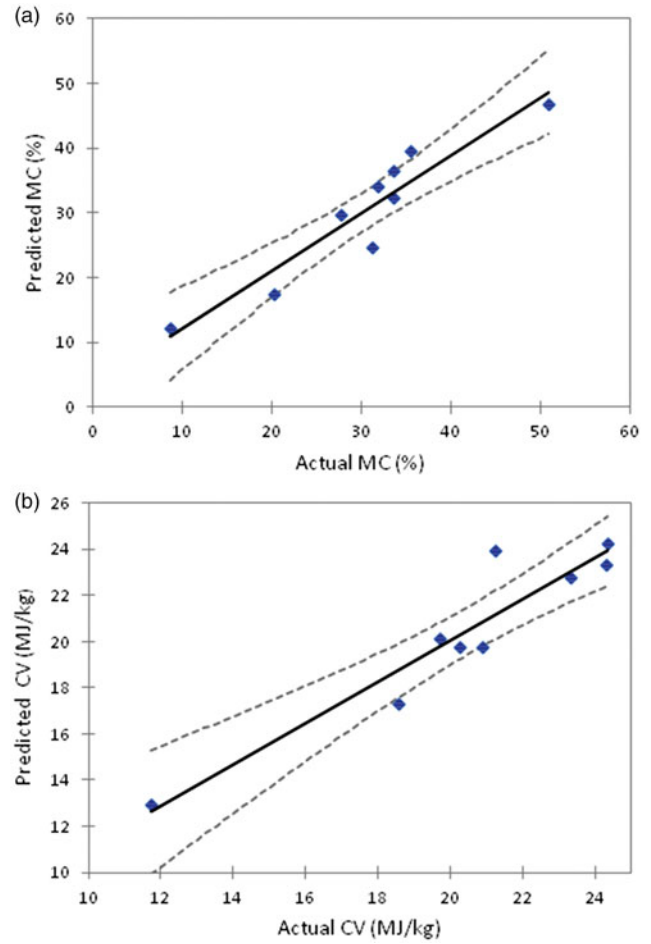


Figure 7. Comparison of linear regression model with experimental results for (a) MC and (b) CV.

physiochemical characteristics and subjected to similar bio-drying process and conditions.

Estimation of performance characteristics

With regards to Taguchi optimization technique, a confirmation experiment is required to predict and verify the improvement of the quality characteristics using the optimal operating variables. The predicted mean of MC (MC_{opt}) and CV (CV_{opt}) at the optimum levels (SB) and (LB) using the control factors – $FW_1Pa_3Pl_3BA_3$ and $FW_1Pa_1Pl_3BA_1$, respectively, were computed with the help of the following predictive equation [33]:

$$MC_{opt} = T_{avrg} + (FW_1 - T_{avrg}) + (Pa_3 - T_{avrg}) + (Pl_3 - T_{avrg}) + (BA_3 - T_{avrg}) \quad (7)$$

$$CV_{opt} = T_{avrg} + (FW_1 - T_{avrg}) + (Pa_1 - T_{avrg}) + (Pl_3 - T_{avrg}) + (BA_1 - T_{avrg}) \quad (8)$$

where MC_{opt} and CV_{opt} are the predicted averages, T_{avrg} is the average of experimental results and $FW_1Pa_3Pl_3BA_3$ and $FW_1Pa_1Pl_3BA_1$ are the average

Table 6. Comparison of predicted and confirmatory experimental results for MC and CV.

Level	Taguchi method			Linear regression method		
	Exp.	Pred.	Error (%)	Exp.	Pred.	Error (%)
MC (%)						
FW ₁ Pa ₁ Pl ₁ BA ₁ ^a	27.77	27.58	0.69	27.77	29.65	6.77
FW ₁ Pa ₃ Pl ₃ BA ₃ ^b	8.59	8.46	1.54	8.59	12.23	42.37
FW ₁ Pa ₃ Pl ₃ BA ₃ ^c	8.59	8.46	1.54	8.59	12.23	42.37
CV (MJ/kg)						
FW ₁ Pa ₁ Pl ₁ BA ₁ ^a	23.34	23.56	0.94	23.34	22.77	2.50
FW ₁ Pa ₁ Pl ₃ BA ₁ ^b	25.50	24.90	2.41	25.50	18.29	39.42
FW ₂ Pa ₂ Pl ₃ BA ₁ ^{c#}	24.35	23.95	1.67	24.35	27.67	13.63

^aControl factors for initial conditions.^bControl factors for optimum conditions.^cControl factors for R3 (highest S/N value for MC).^{c#}Control factors for R5 (highest S/N value for CV).

values of MC and CV with process parameters at their respective optimum levels. The S/N value of MC and CV by the predicted equation for the combination of control factors FW₁Pa₃Pl₃BA₃ was found to be -18.59 and 27.59, whereas the experimental results value for S/N was found to be -18.62 and 28.79, respectively. Additionally, it was observed that the predicted value obtained from the optimal conditions for MC was close to that of R3 (8.59), where the highest value of S/N ratio among the 9 trials was obtained. In contrast, the analysis of CV_{opt} revealed that the predicted value obtained from the optimal conditions was close to that of R5 (24.35), where the highest value of S/N ratio among the 9 trials was obtained. Correlatively, the MC value obtained from the optimal conditions (8.46) and R3 (8.59) were significantly close to each other (Table 6). It is interesting to note that the control factors in R3 and that of MC_{opt} were the same i.e., FW₁Pa₃Pl₃BA₃. This clearly demonstrates that the value of MC and S/N ratio under the optimized conditions are higher than maximum MC and highest S/N ratio obtained in the L₉ array (Table 3). The predicted values and the experimental values were very close to each other. An error of 1.54% and 2.41% for the MC and CV was observed. For reliable statistical analyses, error values must be less than 20% [41] (Table 6). This clearly shows that the error percentages estimated for the optimum conditions by the regression method falls outside the acceptable limits. Consequently, the resulting models obtained using Taguchi technique could be applied effectively to optimize MC and CV to a reasonable accuracy than the regression method.

The performance of the response variables for the verification experiments was better than any other run tested in the orthogonal array. In addition, good agreement was found between the predicted and the verification values. As a result, the Taguchi method

approach is an effective method for determining the optimal processing factor settings to optimize MC and CV. The most significant revelation of the present study was the direct link between the amount of plastic waste content and CV, which is in agreement with the general rule that the CV is proportional to the thermal properties of a material. Second, it is a well-known fact that the CV of a material depends primarily on moisture content. The results further revealed paper waste as the least contributing factor to CV which was evidence in the initial CV determined in Table 1.

Conclusion

The study employed Taguchi method as an experimental design technique to analyze the effects of factors (food waste, paper, plastic, and bulking agent) on moisture content reduction and higher calorific value production by bio-drying process. The optimal conditions for MC and CV were identified as: FW₁Pa₃Pl₃BA₃ (food waste = 15 kg; paper = 8 kg; plastic = 10 kg; and bulking agent = 6 kg) and FW₁Pa₁Pl₃BA₁ (food waste = 15 kg; paper = 2 kg; plastic = 10 kg), respectively. The optimum conditions provided a clear indication in the performance of the response variables. The optimum conditions showed MC decreased by 80% and CV increased by 74%. FW played a significant role in the reduction of MC, whereas Pl was positively correlated to higher CV production. Thus, achieving a higher CV and lower MC would be impossible without the monitoring of the addition of FW and the right proportion of the other waste materials. It is therefore imperative to control the quantity of the waste materials in the entire waste mix during bio-drying process. Additionally, because of the good agreement established between the predicted and the verification experimental values with negligible percent errors, the Taguchi method approach proved effective for determining the optimal condition settings to optimize MC and CV of food waste. In conclusion, the use of food waste in combination with other waste materials by bio-drying process would offer alternative waste management approach and help mitigate environmental pollution from the disposal of biodegradable waste. However, to further enhance the utilization of food waste for higher calorific value production, the optimal design of the factors with different type of food waste of different physico-chemical characteristics needs to be further studied in future.

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