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KOONCHUN LAI[1], SOOKING LIM[2], PEHCHIONG TEH[3], KIMHO YEAP[3]

EFFECTS OF POTENTIAL LEVEL, ROTATION SPEED AND ELECTRODE GAP ON FOOD WASTE RECOVERY USING AN ELECTROSTATIC SEPARATOR

An environmentally friendly method to segregate FW from waste mixture has been presented. The potential level of the separator, the rotation speed and electrode gap are chosen as the independent experimental factors. Second-order quadratic equations have been elaborated to correlate the interactive relationship between the experimental factors and the separation efficiency. The results of the statistical analysis indicate that the electrode gap has immense influence on FW separation. The optimal conditions of segregation have been determined as follows: potential level of 30 kV, rotation speed of 60 rpm, electrode gap of 54 mm and a maximal separation efficiency of 84.0%.

1. INTRODUCTION

Solid waste management has been a global concern for decades. As a result of the unsorted solid waste, huge amount of waste disposed as landfills without prior treatment has caused severe environmental damage. In Malaysia, approximately 95% of waste is landfilled [1]. Landfills in Malaysia are generally full and it is impractical to find new locations. In order to alleviate the landfill problem, the National Strategic Plan for Solid Waste Management in Malaysia has introduced policy on waste management to prioritize waste reduction through processes of reducing, reusing and recycling. However, the policy was impeded by low awareness of citizens [2]. In fact, it is not common to practice source segregation for waste in Malaysia. Most waste is disposed at the disposal site due to the shortage of waste recovery facilities, poor waste management in this country and lack of public awareness [3].

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[1] Centre for Environmental and Green Technology, Universiti Tunku Abdul Rahman, Malaysia, corresponding author, e-mail address: laikc@utar.edu.my

[2] LKC Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Malaysia.

[3] Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Malaysia.

Despite the large disposal space, landfill causes other public nuisances such as air (methane and carbon dioxide), water (leachate) and soil pollution [4]. Proper food waste management is crucial in conserving a clean environment. A high amount of organic material, particularly FW (ca. 45%) can be found in the solid waste in Malaysia [5]. At present, studies of waste recovery of plastic, glass and metal from municipal solid waste have been widely carried out. To date, there is still a lack of progress made for FW recovery [6]. The major problem is due to the notion that FW processing is considered to be a source of composting, which could be a time consuming and non-profitable activity [7]. Since it contains high organic content, however, food waste has the potential to be processed to become a source of biofuel such as ethanol. Because of this reason, an increase of emphasis has recently been placed on the research of FW [8, 9].

Bioethanol is one of the promising alternative energy sources that diminish dependence on the fossil fuel [10]. It could be produced biotechnologically from sugar-rich crops and food scraps. The use of the former feedstock has however received numerous debates on its jeopardousness to food security. The latter, which is inappropriate for human consumption, is considered an ideal source for biofuel production.

In order to promote an environmentally friendly green production, both chemical and biological processes are to be avoided in the segregation of FW from municipal solid waste. Hence, a roll-type electrostatic separator is proposed in this study, to segregate FW from a mixture of other wastes. The scheme of experimental set up for the electrostatic separator is shown in Fig. 1.

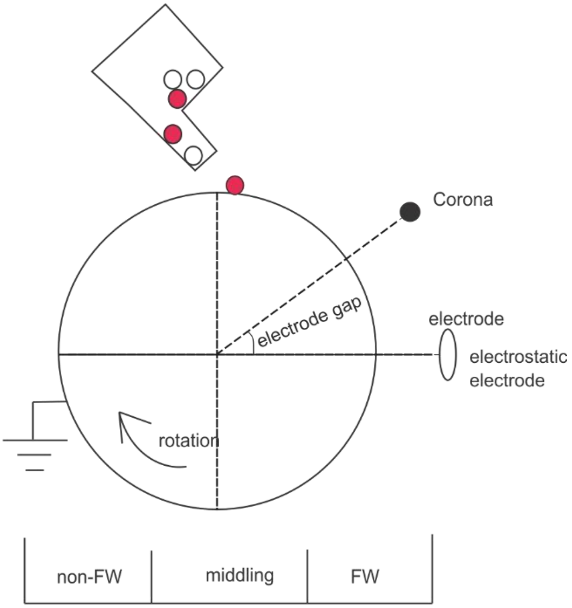

Fig. 1. Electrostatic separator with a fixed electrostatic electrode

In general, FW consists of a higher percentage of moisture [11], making them detachable from plastic and glass during the rotational separation process. The presence of electrostatic charges in the separator is able attract FW which has relatively higher conductivity – therefore, it can ideally sort out FW and non-food waste (non-FW) to different locations. In reality, however, some of these matters may fall in between as middling product. The failure in separating FW from the other waste matters would result in decrease in the separation efficiency. Hence, the middling product is to be minimized in the separation process. In order to optimize the operational conditions for the recovery of FW, response surface method (RSM) has been applied in the process. The RSM is an effective way to be implemented in a multivariable system to determine the interactions among various system factors and to predict the output response. It has been successfully employed to optimize processes [12] and investigate the interactions of process parameters [13].

This study aims to develop an optimized and green method for food waste separation with specific the following objectives:

- to achieve high FW content and/or low middling content,
- to maximize separation yield.

Here, a widely used design of RSM, i.e. the central composite design (CCD) is first applied in order to evaluate the statistically significant factors according to the separation efficiency of FW. The response surfaces are subsequently constructed to maximize the responses. The predicted responses for separation yield and content are finally compared with the evaluated responses using RSM. To the best of our knowledge, this is the first optimization report for FW separation process using electrostatic separators.

2. MATERIALS AND METHODS

Experimental procedures. The sample of test was a 100 g mixture of FW (fruits peel) and non-FW (glass and plastic), in portions of 40 and 60 wt. %, respectively. They were synthetically crushed into small pieces (2.0–4.0 mm). The granular mixture was deposited onto the roller of separator as a monolayer. The distance between the feed system and the top roller position was 50.0 mm. The mass of FW and a portion of unsorted mixture (middling) were collected and measured by a digital precision balance with a resolution of 0.1 g after each run.

Design of experiments. Three independent variables, namely, electrical potential (*A*), rotation speed (*B*) and electrode interval (*C*) were selected according to authors' preliminary study [14]. The analyses of the variables on the separation efficiency of FW and the amount of middling were performed by employing the RSM using Design Expert 8.0.5 software (Stat-Ease, Inc., USA). The central composite design (CCD) was used to evaluate the influence of the variables in 20 experiments, which consisted of 8 factorial points, 6 axial points and 6 replica center points. Table 1 shows the levels and ranges of the three independent variables involved. The CCD design matrix and the corresponding experimental results are summarized in Table 2.

Table 1

Experimental levels of independent process factors

Level	Factor		
	A [kV]	B [rpm]	C [mm]
Low (–1)	20.00	60.00	50.00
Center (0)	25.00	75.00	65.00
High (1)	30.00	90.00	80.00

Table 2

Central composite design for various experimental conditions

Standard. order	Factor			Response S_1 Separation efficiency [%]		Response S_2 Middling [%]	
	A [kV]	*B* [rpm]	*C* [mm]	Actual	Predicted	Actual	Predicted
1	20.00	60.00	50.00	76.5	76.60	15.7	16.22
2	20.00	90.00	50.00	74.7	74.11	18.3	18.51
3	30.00	60.00	50.00	84.0	83.42	12.9	13.33
4	30.00	90.00	50.00	77.9	77.18	15.3	15.43
5	20.00	60.00	80.00	58.6	58.62	35.5	35.88
6	20.00	90.00	80.00	57.2	57.09	37.2	37.27
7	30.00	60.00	80.00	64.3	64.19	33.3	33.60
8	30.00	90.00	80.00	59.7	58.91	34.8	34.79
9	25.00	49.77	65.00	80.4	80.41	18.3	17.57
10	25.00	100.23	65.00	72.9	73.87	20.5	20.50
11	16.59	75.00	65.00	69.6	69.61	20.9	20.44
12	33.41	75.00	65.00	75.9	76.87	16.2	15.94
13	25.00	75.00	39.77	71.6	72.33	22.5	21.98
14	25.00	75.00	90.23	41.6	41.85	55.0	54.80
15	25.00	75.00	65.00	76.7	75.62	17.0	18.24
16	25.00	75.00	65.00	75.4	75.62	18.4	18.24
17	25.00	75.00	65.00	74.7	75.62	19.2	18.24
18	25.00	75.00	65.00	76.7	75.62	17.1	18.24
19	25.00	75.00	65.00	74.9	75.62	19.2	18.24
20	25.00	75.00	65.00	75.5	75.62	18.4	18.24

A quadratic polynomial equation was applied to identify the critical points and to express the response of the separation according to the following relation:

$$S = \beta_0 + \sum_{i=1}^{p} \beta_i X_i + \sum_{i=1}^{p} \beta_{ii} X_i^2 + \sum_{1 \le i \le j}^{p} \beta_{ij} X_i X_j + e_i \ [\%] \tag{1}$$

where S represents the response of separation efficiency or amount of middling percentage, β_0 the constant coefficient, X_i, X_j are independent variables, β_i, β_{ii}, β_{ij} are the coefficients for linear, quadratic and interaction equations, respectively, and e_i is a constant for error. Analysis of variance (ANOVA) was employed to assess the fitted quality of the model and statistical significance of the regression coefficients. ANOVA compares the change of variable levels and the variation due to random errors of response measurement [15]. Besides, the Pareto analysis was applied to calculate the vital percentage of each significant factor towards the response as follows:

$$P_i = \frac{\beta_i^2}{\sum \beta_i^2} \times 100 \tag{2}$$

where P represents the importance level of each variable and β represents each polynomial coefficient stated in Eq. (1).

Experimental procedures. The separation experiments were carried out with an earth-grounded roller type electrostatic separator. As shown in Fig. 1, an ionizing needle electrode powered by a high voltage power source (up to 35 kV) was placed at one side of the separator for generation of corona discharge. An electrostatic plate electrode was connected beneath, providing the non-discharging electrostatic charge. When the separator delivered particles through the ionizing zone generated by the electrodes, the FW particles lose their charge rapidly, avoiding them from being pinned for a longer time than the less conductive non-FW particles. With the continuous rotation from the roller, FW particles were subjected to a centrifuge force which was larger than the pinning force and thrown off the roller to FW collection tank. The non-FW granules remained pinned to the roller due to the larger pinning force applied on them. Eventually they fell off at the non-FW tank. The particles that fell to the middling tank were used as the indicator of recovery efficiency [14]. The distance between the surface of the roller and the corona electrode was set at 60 mm to generate a wide pinning zone. The speed of the roller was controlled by a variable speed geared motor with a power consumption of 40 W (Peei Moger, Taiwan). The ambient temperature was recorded as 24–28 °C with the relative humidity of 50–60%.

3. RESULTS AND DISCUSSION

3.1. STATISTICAL ANALYSIS AND MODEL FITTING

Table 2 lists the experimental design matrix with the corresponding evaluated values and predicted values suggested by RSM for both the FW separation efficiency and percentage of middling product. In order to demonstrate the empirical correlation between response S_1 and the independent factors, a second-order equation has been used as follows:

$$S_1 = -41.912 + 3.324A - 0.244B + 3.206C - 0.013AB + 1.056\times10^{-3}BC$$

$$-4.167\times10^{-3}AC - 0.034A^2 + 2.387\times10^{-3}B^2 - 0.029C^2 \quad [\%] \qquad (3)$$

where S_1 is the separation efficiency of FW in terms of actual factors.

Besides, a polynomial equation was used for the response S_2:

$$S_2 = 115.897 - 0.315A - 0.049B - 3.441C - 0.667\times10^{-3}AB - 1.000\times10^{-3}BC$$

$$+\ 2.000\times10^{-3}AC - 0.667\times10^{-3}A^2 + 1.261\times10^{-3}B^2 + 0.032C^2 \quad [\%] \qquad (4)$$

where S_2 is the amount of the middling in term of percentage.

Table 3

ANOVA results for quadratic model of S_1

Source	Sum of squares	Degree of freedom	Mean square value	*F*-value	*p*-value	Remarks
Model	1885.29	9	209.48	258.17	<0.0001	significant
A	63.70	1	63.70	78.51	<0.0001	significant
B	51.47	1	51.47	63.44	<0.0001	significant
C	1121.41	1	1121.41	1382.10	<0.0001	significant
AB	7.03	1	7.03	8.67	0.0147	significant
AC	0.78	1	0.78	0.96	0.3496	
BC	0.45	1	0.45	0.56	0.4730	
A^2	10.21	1	10.21	12.59	0.0053	significant
B^2	4.15	1	4.15	5.12	0.0471	significant
C^2	618.60	1	618.60	762.40	<0.0001	significant
Residue	8.11	10	0.81			
Lack of fit	4.36	5	0.87	1.16	0.4370	not significant
Pure error	3.75	5	0.75			
Cor Total	1893.41	19				
R-squared: 0.9957; Adj *R*-squared: 0.9919; Pred *R*-square: 0.9796; Adeq precision: 65.257.						

Factors with either synergistic or antagonistic effect on the response are decided by the positive or negative signs, respectively, of the regression coefficients. Tables 3 and 4 summarize the ANOVA results for the efficiency of FW separation (S_1) and the percentage of middling (S_2). The model *F*-values of 258.17 and 349.58 for response S_1 and S_2, respectively, imply that both the models are significant. The p-values which are <0.0001 for both responses S_1 and S_2 indicate that the adequacy of the models is within acceptable range. The predicted R-squared value of 0.9796 is in reasonable agreement with the adjusted R-squared value of 0.9919 for S_1. The signal to noise ratio (adequate precision) of 65.257 indicates that the model can be used to navigate the design space. Like S_1, the predicted R-squared of 0.9899 for S_2 is close to the adjusted R-squared of 0.9940. An adequate precision of 72.174 (greater than 4) implies that model S_2 could also be used in the design of space navigation [16].

Table 4

ANOVA results for quadratic model of S_2

Source	Sum of squares	Degree of freedom	Mean square value	F-value	p-value	Remarks
Model	2076.92	9	230.77	349.58	<0.0001	significant
A	24.53	1	24.53	37.16	0.0001	significant
B	10.37	1	10.37	15.71	0.0027	significant
C	1300.28	1	1300.28	1969.71	<0.0001	significant
AB	0.020	1	0.020	0.030	0.8653	
AC	0.18	1	0.18	0.27	0.6129	
BC	0.41	1	0.41	0.61	0.4516	
A^2	0.00	1	0.00	0.01	0.9394	
B^2	1.16	1	1.16	1.76	0.2143	
C^2	731.62	1	731.62	1108.28	<0.0001	significant
Residue	6.60	10	0.66			
Lack of fit	1.87	5	0.37	0.40	0.8338	not significant
Pure error	4.73	5	0.95			
Cor total	2083.53	19				
R-squared: 0.9968; Adj R-squared: 0.9940; Pred R-square: 0.9899; Adeq precision: 72.174.						

The good correlations $R^2 = 0.9957$ and $R^2 = 0.9968$ shown in Figs. 2a and 2b, respectively, indicate that there are not much difference between the real values and the theoretical values. The p-values indicate the significance effect of the model, particularly when p-value is lower than 0.05. It is apparent that the models of S_1 and S_2 are highly significant as the p-values are <0.0001 (Tables 3 and 4). In addition, the quantitative impact of three independent factors is determined by their p-values. In the S_1 model, the significant model terms are identified as A, B, C, AB, A^2, B^2, C^2 with p-values <0.05 (Table 3). All the independent factors, i.e. A – potential level, B – rotation speed, C – electrode gap and second-order effect of C have high significant effect on the separation efficiency for p <0.0001. On the other hand, parameters of A, B, C, C^2 are significant variables for model S_2. It is worthwhile noting that the mass of middling could be mostly influenced by the C factor and its second-order effect, but not the interaction effects amongst the A, B and C factors.

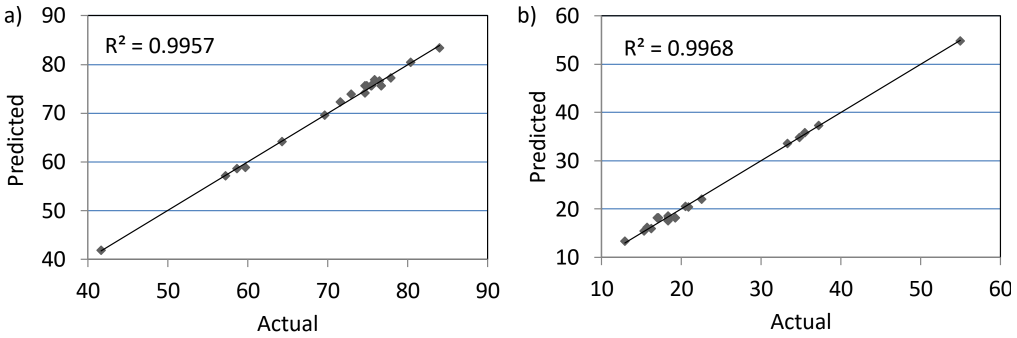

Fig. 2. Predicted values versus actual values (%): a) separation efficiency, b) middling percentage

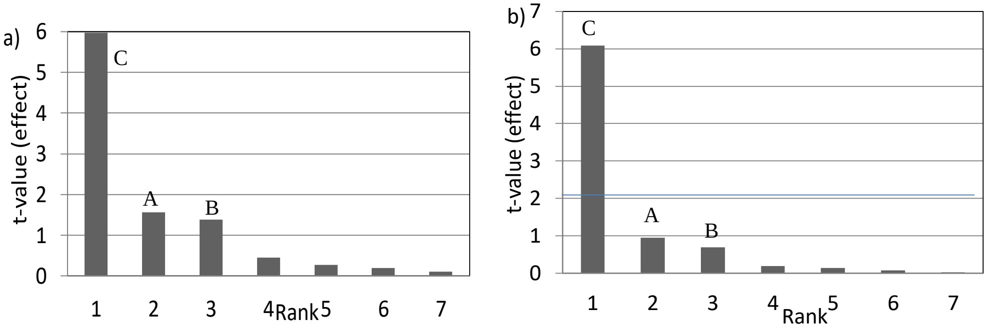

Fig. 3. Pareto chart for: a) separation efficiency, b) middling percentage; *t*-value limit 2.131

To further confirm the influence of considered factors on the separation efficiency, the Pareto analysis in the form of the Pareto chart was used to determine the main effects of the three independent factors. As can be seen from Fig. 3a, all three factors are statistically significant for the S_1 model. As shown in Fig. 3b, the Pareto chart shows that the result for the middling mass is similar to that of the separation efficiency, i.e. the potential level (*A*), rotation speed (*B*), and electrode gap (*C*) are the most significant factors which affect the response model. In particular, Fig. 3a shows that the potential level gives a positive effect whereas the rotation speed and the electrode gap give negative effects to the separation efficiency. As can be observed in Fig. 3b, the three factors exhibit an overall opposite effect on the middling percentage. This means that the separation efficiency can be enhanced by minimizing the middling percentage. The result is in close agreement with the experiments which show that the recovery of biomass increases with decreasing amount of unsorted middling for each fixed amount of test sample (100 g). Therefore, model S_2 is not included for further discussion, whereas model S_1 would be focused in the next section for performance optimization.

3.2. SURFACE PLOT ANALYSIS

Three-dimensional surface plots were generated to further investigate the interactions among the independent factors *A*, *B*, *C* and the separation efficiency of waste. The combined effects of factors *A* and *B* in the separator with the electrode gap of 65 mm is shown in Fig. 4a. The result shows that the separation efficiency increases upon increasing potential level and, likewise, decreases when the speed of the roller rotation increases. The surface plot indicates that the potential level has a synergistic effect on corona charging of the waste granules. For instance, the separation efficiency increases from 69.6% to 76.7% upon increasing potential level from 16.59 kV to 25.0 kV when the rotation speed is maintained at 75 rpm. We assign this result to the non-uniformity of sizes found in the granular test sample. Hence, a larger Coulomb force is required to treat the larger granules. It was generally known that the Coulomb forces relate positively with the supplied potential. The rotation speed, on the other hand, gives an antagonistic effect to the separation performance. The separation efficiency decreases from 80.4% to 72.9% when the rotation speed increases from 49.77 rpm to 100.23 rpm at 25 kV potential level. This is because the middling percentage increases with increasing rotation speed (Table 2). The relationship between the middling product and the rotation speed found in our experiments is in good agreement with the result obtained by Wu et al. [17]. Our experiment shows that the maximum separation efficiency of waste is obtained at the minimum rotation speed (60 rpm) with potential level closed to 30.0 kV.

Figure 4b demonstrates the correlated effects of factors *A* and *B* on the separation efficiency with a constant speed of 75 rpm. It is obvious that the separation efficiency increases upon increasing potential level, indicating a stronger electrostatic field enhances the induction charging of conductive granules. The percentage of the separation efficiency increases when the electrode gap changes from 50 mm to 60 mm (Fig. 4b). Beyond 60 mm, however, the efficiency decreases progressively. This suggests that a gap range of 50–60 mm allows a uniformly extensive charge distribution to be generated to enhance separation efficiency [17]. Figure 4b also demonstrates that the potential level and electrode gap have the synergistic effect on the separation efficiency, and its highest value could be achieved at the maximum potential level (30 kV) with proper spacing of electrodes approximately closed to 60 mm.

With a fixed potential level of 25 kV, the combined effects of factors *B* and *C* on the separation efficiency are shown in Fig. 4c. It is apparent that the separation efficiency of waste decreases upon increasing rotation speed when the electrode gap is less than 60 mm. This is mainly due to the increase of unsorted middling product which is in direct proportion with the rotation speed. Figure 4c also shows that the separation efficiency decreases with increasing electrode gap beyond 60 mm (cf. Fig. 4b). We attribute the reduction in separation efficiency to the weaker charge on the test granules. The highest value of the separation efficiency is achieved at the minimum rotation speed (60 rpm) with the electrode gap approximately close to 60 mm.

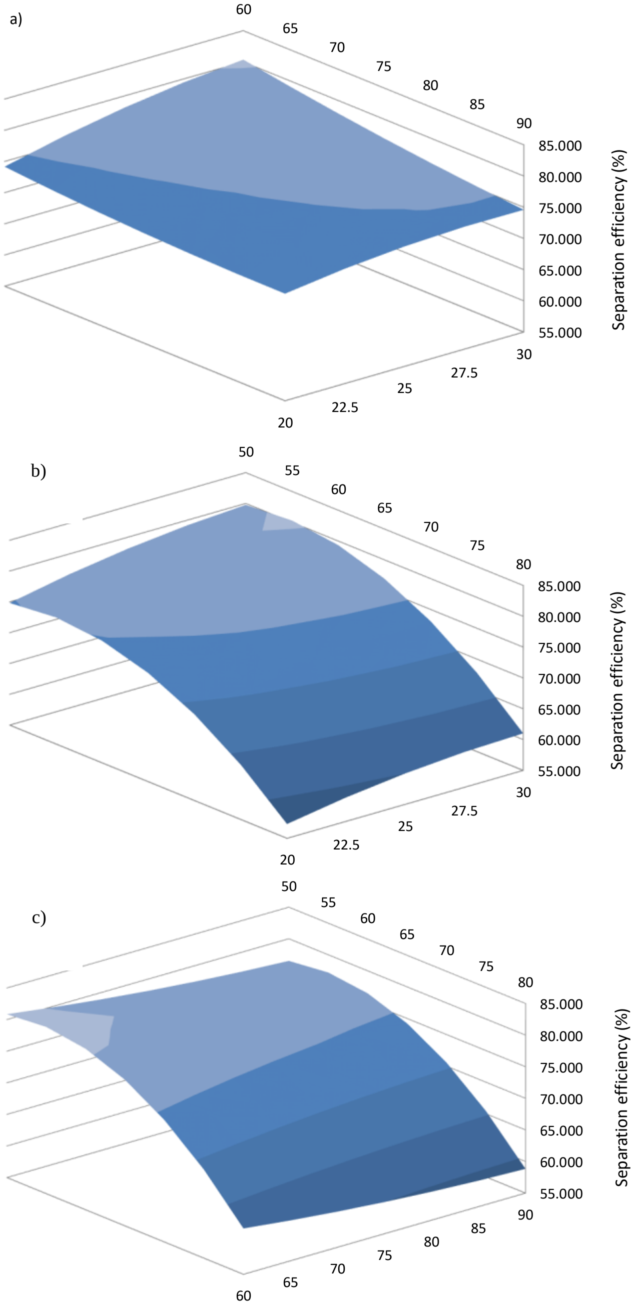

Fig. 4. Surface plots for combined effects of two independent factors on the separation efficiency:
a) potential level (lower axis, kV) and rotation speed (upper axis, rpm), electrode gap 65 mm;
b) potential level (lower axis, kV) and electrode gap (upper axis, mm), rotation speed 75 rpm;
c) rotation speed (lower axis, rpm) and electrode gap (upper axis, mm), potential level 25 kV)

3.3. MODEL OPTIMIZATION AND VALIDATION

The optimal conditions for maximum separation yield (84.0%) can be obtained when the potential level is at 30 kV, roller rotation 60 rpm and electrode gap 54 mm (Table 1). At the optimum conditions, the middling percentage of 12.7% was estimated. In order to validate the statistical experimental strategies, experiments have been performed at triplicate. At the specified optimum conditions, an average separation efficiency of 83.6±0.7% was achieved. The experimental value agrees closely with the predicted value. Hence, our model and the application of RSM in optimizing the FW separation from waste mixture have been validated.

4. CONCLUSION

Electrostatic separation process has been applied to segregate the reusable food waste from a mixture of other waste materials such as plastics and glasses. We have applied a widely used response surface method, i.e. the central composite design CCD, to optimize the separation conditions. From the analysis, it was found that the electrode gap is an essential parameter in determining the separation efficiency of FW. Variation at the potential level and rotation speed, on the other hand, show little effect on the efficiency. By employing CCD on the separation process, we found that optimum performance with maximum yield of 84.0% and minimum middling of 12.7% can be achieved when the potential level is at 30 kV, rotation speed 60 rpm, and electrode gap 60 mm. We have also validated the model that we have developed with experimental results. The theoretical results agree very well with those obtained experimentally.

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