# Models for Higher Heating Value Evaluation of Refuse-Derived Fuel from On-nut Composting Plant, Bangkok

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## Abstract

Refuse-derived fuel (RDF) in this research was municipal solid waste composting residue from On-nut Composting Plant in Bangkok, Thailand. The purpose of the research was to study the relationships between the RDF heating value and its physical and chemical characteristics in order to develop a mathematical model for predicting a higher heating value (HHV). Regression analysis was performed on fourteen RDF data samples collected from June 2009 to November 2009. The results revealed that the developed model, based on physical composition, gave a HHV of 5,383.541 + 0.457 (plastic)$^2$ with a coefficient of determination ($r^2$) value of 0.726 and a mean absolute percentage error (MAPE) value of 3.41%. For proximate analysis, none of the independent variables correlated with the HHV at a significance level of 0.05. The developed model, based on ultimate analysis, gave a HHV of 135.505 (carbon) with $r^2$ of 0.716 and MAPE of 9.22 %. In conclusion, the model based on physical composition gave a more accurate prediction of RDF HHV than the model based on ultimate analysis.

*Key words:* refuse-derived fuel (RDF)/ heating value/ mathematical model/ municipal solid waste/ composting residue

## 1. Introduction

Municipal solid waste (MSW) generated in Thailand increased from 14.72 million tons in 2007 (40,332 tons/day) to 15.03 million tons in 2008 (41,064 tons/day) (not include some of solid waste that was separated before discarding). In 2008, about 8,780 tons/day of municipal solid waste was collected in Bangkok (Pollution Control Department, 2008; 2009). The solid waste disposal by sanitary landfill is generally used in Thailand. Moreover solid waste generation rate has continuously increased and caused the landfill lifespan shorter than predicted. Therefore to prolong the landfill lifespan, solid waste could be treated before disposal such as by composting. Composting can significantly decrease the solid waste volume to be disposed in sanitary landfill. By-product from composting is refuse-derived fuel (RDF), it is the residue from screening in composting process. Most of RDF is plastic which is non-degradable or very slowly degradable. RDF can be used as fuel in some factories because of its high calorific value and low cost compared to other types of fuel. More than 259 tons/day of RDF are generated from On-nut Composting Plant, Bangkok.

The heating value of the organic component in MSW can be determined in various methods such as determined by using a full scale boiler as a calorimeter, by using the oxygen bomb calorimeter, and by calculation (Tchobanoglous et al, 1993). Nevertheless from the difficulty in instrumenting full scale boiler, the researchers often select the other two methods to determine the heating value. Compared to the oxygen bomb calorimeter method, calculation by mathematical model based on physical composition is more convenient and more economical. However, with recent development in element analyzers and

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other equipment, the ultimate analysis and proximate analysis may be more convenient to obtain the heating value. Therefore, this research was intended to study the relationships between heating value and physical composition, heating value and proximate analysis, and heating value and ultimate analysis of RDF from MSW composting plant in order to establish the mathematical models for calculating its heating value.

## 2. Methodology

The RDF in this research was residue (size larger than 70 mm) from On-nut Composting Plant, Bangkok. A total of 14 RDF samples were collected during June to November 2009 for analysis. Their physical compositions (plastic, wood, food waste, paper, rubber, leather, compost and textile), air dry moisture, proximate analysis (residual moisture, combustible matter and ash), ultimate analysis (carbon, hydrogen, oxygen, nitrogen, sulfur, and chlorine), and heating value by using the oxygen bomb calorimeter were analyzed. The data of these samples were used for developing mathematical models.

### *2.1 RDF sampling and physical composition analysis*

RDF approximately 400 kg was randomly sampled from the rejected part of the composting process at On-nut Composting Plant. RDF was piled and mixed. Then quartering technique was used to reduce the sample size until RDF sample decreased to about 50 kg. This sample is called gross sample. Physical composition of gross sample was determined by hand sorting of plastic, paper, compost, textile, wood, food waste, rubber and leather. Weight of each component was used for calculation of the wet weight percentage. Air dry moisture of each component was analyzed according to ASTM E 949-88 (reapproved 2004) by drying in the oven under controlled temperature condition not greater than 40 ˚C until the sample weight was constant. Then air-dried weight percentage of physical composition was calculated. Approximately 2 kg of RDF was randomly sampled from gross sample which is called laboratory sample.

### *2.2 Preparing RDF laboratory sample for analysis*

RDF laboratory sample was prepared according to ASTM E 829-94. The laboratory RDF sample was air-dried in the oven. Then the particle size of the sample was reduced by shredding to approximately 0.5 mm. This is called air-dried finely ground laboratory sample. At least 50 g of the air-dried finely ground laboratory sample was separated and kept in a sample container having an air-tight seal. This is called air-dried analysis sample. It was used for proximate, ultimate and heating value analyses.

### *2.3 Proximate analysis*

Residual moisture was determined according to ASTM E 949-88 (reapproved 2004) by drying the air-dried analysis sample at 107 ± 3 ˚C for 1 hour. Ash was determined according to ASTM E 830-87 (reapproved 2004) by gradually heating the air-dried analysis sample to ignition at 575 ± 25 ˚C, cool down, and weigh until the ash weight was constant. The combustible matter was calculated as follows:

$$\text{Combustible matter (\%)} = 100 - (\text{\% residual moisture} + \text{\% ash})$$

### *2.4 Ultimate analysis*

Carbon, hydrogen and nitrogen of plastic, paper, textile, food waste, wood, rubber and leather were analyzed by the Perkin Elmer Element analyzer (model PE2400). Carbon, hydrogen and nitrogen of each sample were calculated according to its physical composition.

Total sulfur was analyzed according to ASTM E 775-87 (reapproved 2004) by precipitation as $BaSO_4$ from the bomb calorimeter washings. The precipitate was filtered, ashed and weighed.

Sample solution for total chlorine analysis was prepared by oxygen bomb method according to ASTM E 776-87 (reapproved 2004). The chloride in the sample solution was analyzed by Argentometric or Mohr method according to Standard Methods for the Examination of Water and Wastewater (APHA et al., 2005). Then the weight % of total chlorine was calculated.

The weight percentage of oxygen was calculated as follows:

$$O\ (\%) = 100 - (\%\ C + \%\ H + \%\ N + \%\ S + \%\ Cl + \%\ ash)$$

### *2.5 Heating value*

Heating value was determined according to ASTM E 711-87 (reapproved 2004) by igniting approximately 1 g of air-dried analysis sample in bomb calorimeter. The heating value was determined with the acid, sulfur and the fused wire corrections.

### *2.6 Data analysis*

The relationships between higher heating value (HHV) and physical compositions, proximate analysis and ultimate analysis were analyzed. Models for HHV determination from physical composition, proximate analysis and ultimate analysis were developed by using regression analysis. Stepwise regression method was used to select independent variables which included forward and backward selection methods to obtain the highest $r^2$ of the predicting model. The statistical significance was set at entry level of 0.05 and removal level of 0.10. The variables were defined as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_k x_k$$

where: $Y$ = higher heating value (HHV) (kcal/kg)
$x_1, x_2, \ldots, x_k$ = independent variables (wt %)
$\beta_0$ = y-axis intercept
$\beta_1, \ldots, \beta_k$ = regression coefficients

## 3. Results and Discussion

### *3.1 Physical composition*

From results of physical compositions, as shown in Table 1, plastic, compost, food waste, wood, textile, paper, rubber and leather were in the ranges of 25.38-70.23, 19.01-47.84, 0.12-13.63, 0-11.49, 0-12.19, 0-4.36, 0-5.83 and 0-3.38 %, respectively.

Among the physical compositions, the main components were plastic (56.21 %) and compost (31.43 %). The total of these two components was 87.64 %. It implies that heating value is largely provided by these two components. Plastic in Taiwan RDF produced by MSW sorting and shredding (size larger than 100 mm) is also the highest portion at 57.81 % (Chang et al, 1997) which is nearly the same as plastic content in the

RDF from On-nut Composting Plant. This component is mainly from plastic packaging.

**Table 1:** Properties of RDF samples from On-nut MSW composting process

| | Percentage by weight (air-dry basis) | | |
|---|---|---|---|
| | Range | Average | S.D. |
| **Physical composition** | | | |
| Plastic | 25.38 – 70.23 | 56.21 | 12.00 |
| Compost | 19.01 – 47.84 | 31.43 | 7.15 |
| Food waste | 0.12 – 13.63 | 5.97 | 4.86 |
| Wood | 0 – 11.49 | 3.23 | 3.55 |
| Textile | 0 – 12.19 | – | – |
| Paper | 0 – 4.36 | – | – |
| Rubber | 0 – 5.83 | – | – |
| Leather | 0 – 3.38 | – | – |
| **Proximate analysis** | | | |
| Moisture | 2.18 – 3.28 | 2.93 | 0.30 |
| Ash | 19.76 – 29.31 | 24.48 | 3.31 |
| Combustible matter | 68.22 – 76.99 | 72.58 | 3.26 |
| **Ultimate analysis** | | | |
| Carbon | 46.63 – 59.85 | 55.16 | 4.02 |
| Hydrogen | 6.34 – 8.71 | 7.89 | 0.70 |
| Oxygen | 1.96 – 17.01 | 10.32 | 4.79 |
| Nitrogen | 1.08 – 1.45 | 1.30 | 0.10 |
| Sulfur | 0.05 – 0.18 | 0.12 | 0.03 |
| Chlorine | 0.50 – 1.20 | 0.73 | 0.17 |
| HHV (kcal/kg) | 5,811.4 – 7,958.0 | 6,888.1 | 644.3 |

## *3.2 Chemical composition*

### *3.2.1 Proximate analysis*

From results of proximate analysis, as shown in Table 1, residual moisture, ash and combustible matter were in the ranges of 2.18-3.28, 19.76-29.31 and 68.22-76.99 %, respectively.

Because the proximate analysis of the RDF from On-nut Composting Plant was based on air-dry weight while the proximate analysis of Taiwan RDF in Chang et al (1997) research was based on wet weight. Therefore, the average value of moisture content of RDF in this research (2.93 %) is much lower than Taiwan RDF (40.28 %).

### *3.2.2 Ultimate analysis*

From results of ultimate analysis, as shown in Table 1, carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine were in the ranges of 46.63-59.85, 6.34-8.71, 1.96-17.01, 1.08-1.45, 0.05-0.18 and 0.50-1.20 %, respectively.

It was found that carbon, hydrogen and oxygen were the main elements of the RDF samples with the average values of 55.16, 7.89, and 10.32 %, respectively, while the minor elements of the RDF samples were nitrogen, sulfur, and chlorine with the average values of 1.30, 0.12 and 0.73 %, respectively.

Because carbon is the largest element of RDF sample, therefore a main portion of RDF samples is combustible matter. The average value of chlorine in this research (0.73 % air dry weight) is higher than Taiwan RDF (0.23 % wet weight) (Chang et al, 1997). Chlorine plays an important role in dioxin formation. However, its upper value is still not higher than those biomass fuels such as triticale (cereals) and grass ( 2 % Cl by dry weight) (van Loo and Koppejan, 2008).

### *3.3 Heating value*

The HHV of RDF samples ranged from 5,811.4 to 7,958.0 kcal/kg air dry sample with the average value of 6,888.1 kcal/kg air dry sample. They are higher than the HHV of Taiwan RDF which ranged from 2986.0 to 4749.0 kcal/kg wet sample with the average value of 3715.9 kcal/kg wet sample (Chang et al, 1997). The difference in calculation bases between these two studies is a main reason causing the heating value to be different.

### *3.4 Model for HHV determination*

#### *3.4.1 Model based on physical composition*

1) Relationship between HHV and physical composition

Four independent variables, namely textile, paper, rubber and leather were not found in several samples, therefore these variables were not included in the correlation analysis. The data of HHV and physical composition, (plastic, compost, food waste, wood, and residual moisture), were used for correlation analysis.

It was found that HHV and plastic had significant correlation ($p < 0.001$), but HHV and compost, HHV and wood, HHV and food waste, and HHV and residual moisture had insignificant correlation ($p$ = 0.260, 0.133, 0.072 and 0.271, respectively), as shown in Figure 1. Therefore, the relationship of HHV and plastic is in a linear form with correlation coefficient (r) of 0.831. However, the other form of relationship between HHV and plastic were also investigated. It was found that relationship of HHV and plastic is in a quadratic form with r of 0.852.

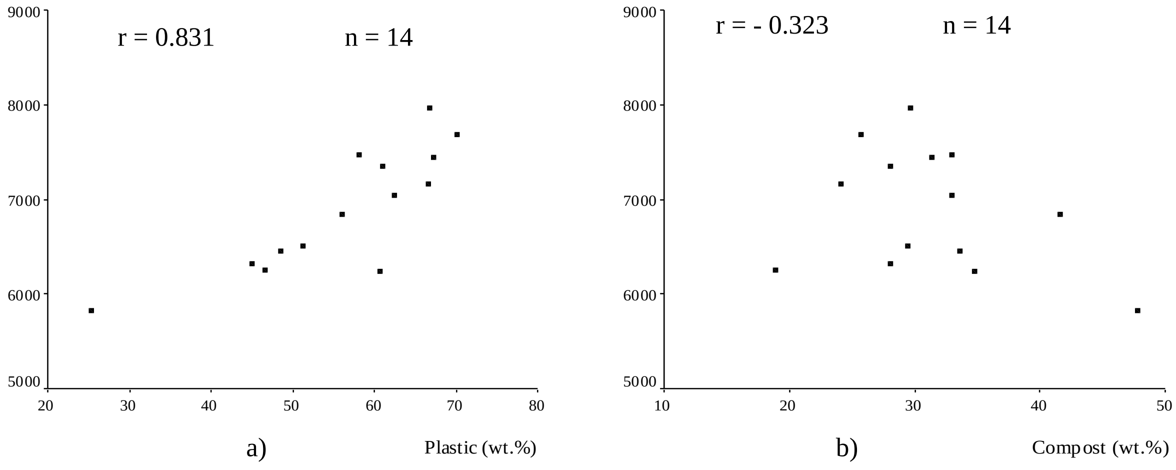

**Figure 1** Scatter plots of relationship between HHV and physical compositions: a) relationship between HHV and plastic, b) relationship between HHV and compost,

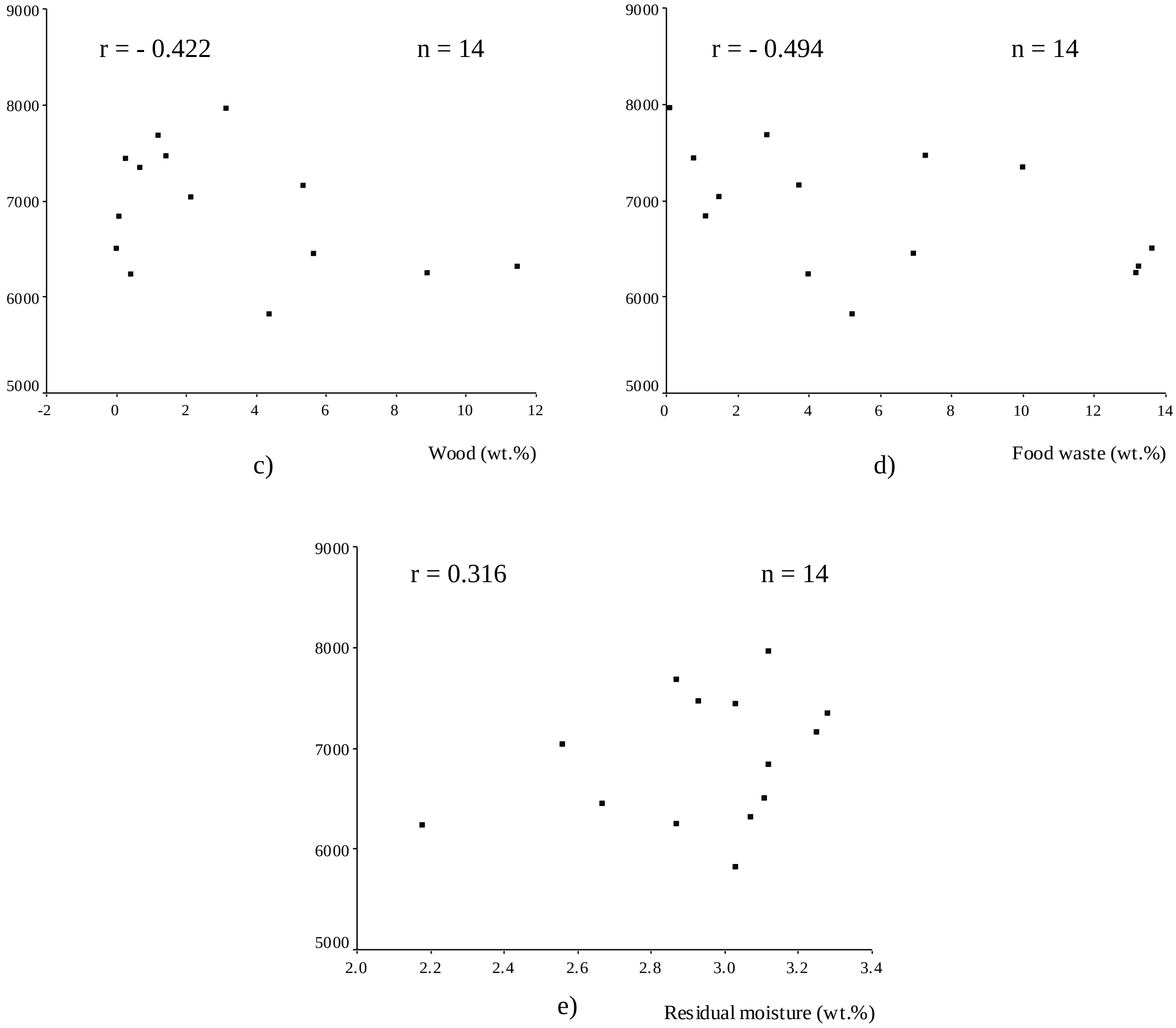

**Figure 1** (continued) Scatter plots of relationship between HHV and physical compositions: c) relationship between HHV and wood, d) relationship between HHV and food waste, and e) relationship between HHV and residual moisture

2) Regression analysis

2.1 Linear regression

In linear regression analysis, plastic was an independent variable while HHV was a dependent variable. The result reveals that the coefficient of determination ($r^2$) is 0.690. This implies that the independent variable (plastic) influences the dependent variable (HHV) at 69 per cent. From hypothesis test of the overall regression coefficient of linear model, it was found that p- value is less than 0.001. While hypothesis test of the individual coefficient of the regression indicates that p-value is also less than 0.001. Therefore, the developed model in linear form is as follows: HHV = 4381.552 + 44.591 plastic. However, this model did not meet all the residual assumption requirements of the linear regression, thus this model cannot be accepted.

2.2 Non-linear regression

By using a non-linear regression analysis, it was found that the relationship between plastic and HHV is in a quadratic form. Therefore, plastic was transformed by raising to the power of 2, new variable was $(\text{plastic})^2$. In the development of regression model, $(\text{plastic})^2$ was taken as an independent variable while HHV was a dependent variable. The value of r between $(\text{plastic})^2$ and HHV is 0.852 and $r^2$ is 0.726. From hypothesis test of the overall regression coefficient of quadratic model, it was found that p-value is less than 0.001. And hypothesis test of the individual of the regression coefficient indicates that p-value is also less than 0.001. Therefore, the developed model in quadratic form is as follows: $\text{HHV} = 5{,}383.541 + 0.457\,(\text{plastic})^2$. Moreover, this model met all the residual assumption requirements of the regression. The model indicates that HHV is a function of plastic content in RDF. While other components such as compost, food waste, wood and residual moisture are excluded in this model. This may possibly be due to the low content of compost, food waste, wood and residual moisture in RDF.

### *3.4.2 Model based on proximate analysis*

1) Relationship between HHV and proximate analysis

The data of HHV and proximate analysis were used for correlation analysis. There is no relationship between HHV and combustible matter, HHV and ash, and HHV and residual moisture at a significance level of 0.05. Therefore, the mathematical model based on proximate analysis cannot be developed.

### *3.4.3 Model based on ultimate analysis*

1) Relationship between HHV and ultimate analysis

From correlation analysis it was found that HHV and carbon, HHV and hydrogen, and HHV and chlorine had significant correlation ($p < 0.01$), but HHV and oxygen, HHV and nitrogen, and HHV and sulfur had insignificant correlation ($p = 0.016$, 0.520 and 0.062, respectively), as shown in Figure 2. There is also some relationship among them (carbon, hydrogen, and chlorine) which is not in accordance with the assumption requirements of the linear regression. Among carbon, hydrogen, and chlorine in RDF samples, carbon is the main element of RDF sample. Besides, carbon provides the thermal energy (van Loo and Koppejan, 2008). Therefore, only carbon was selected as an independent variable in the model. It shows that the relationship of HHV and carbon is in a linear form with r of 0.846. However, the other form of relationship between HHV and carbon was also investigated. It was found that the relationship between HHV and carbon is in a quadratic form with r of 0.850.

2) Regression analysis

2.1 Linear regression

In linear regression analysis, carbon was an independent variable while HHV was a dependent variable. The result reveals that $r^2$ is 0.716. This implies that the independent variable (plastic) influences the dependent variable (HHV) at 71.6 per cent. From hypothesis test of the overall regression coefficient of linear model, it was found that p-value is less than 0.001. While hypothesis test of the individual coefficient of the regression indicates that p-value is also less than 0.001. Therefore, the developed model in linear form is as follows: $\text{HHV} = 135.505\,\text{carbon}$. Moreover, this model met all the residual assumption requirements of the linear regression.

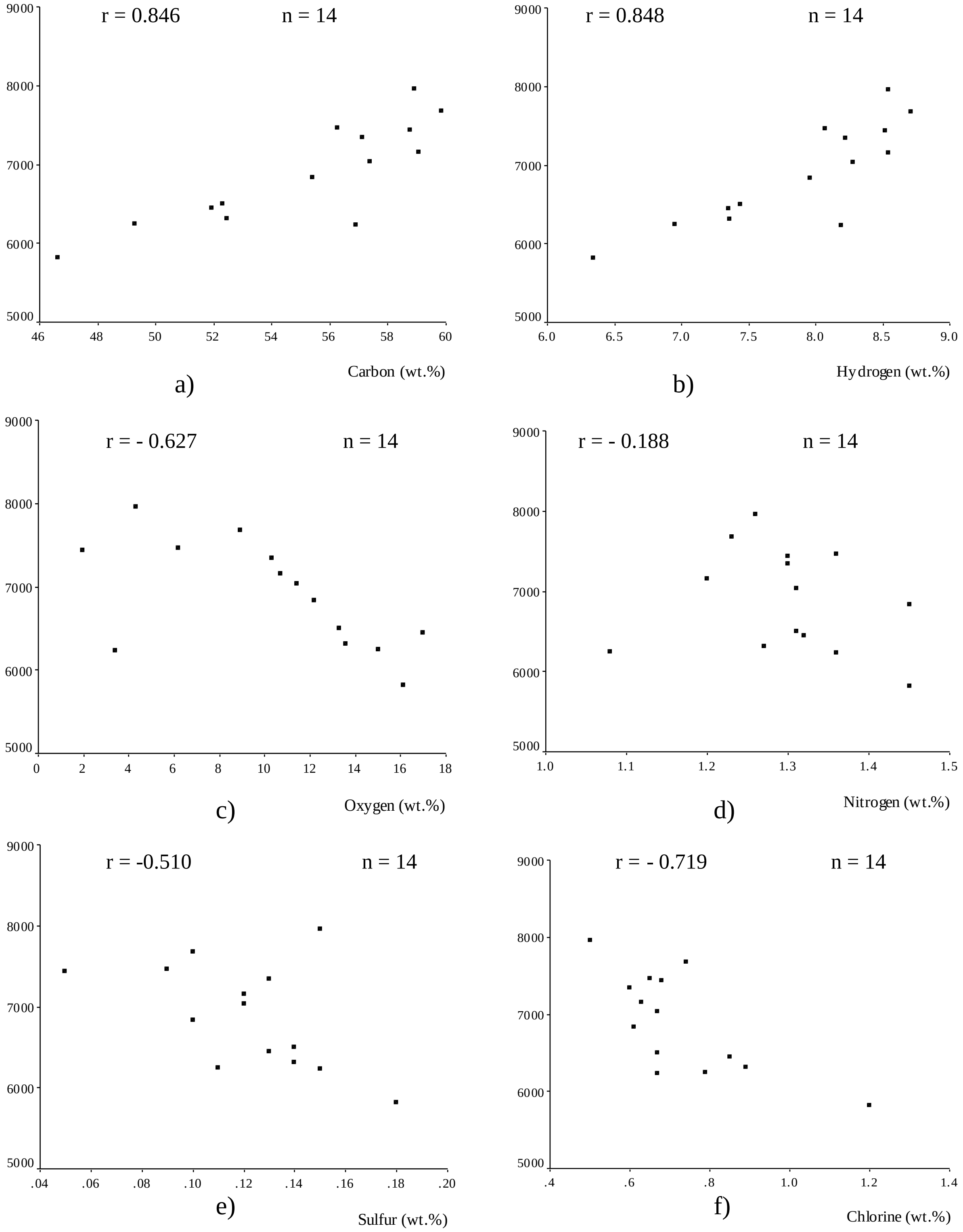

**Figure 2** Scatter plots of relationship between HHV and ultimate analysis: a) relationship between HHV and carbon, b) relationship between HHV and hydrogen, c) relationship between HHV and oxygen, d) relationship between HHV and nitrogen e) relationship between HHV and sulfur, and f) relationship between HHV and chlorine

2.2 Non-linear regression

By using a non-linear regression analysis, it was found that the relationship between carbon and HHV is in a quadratic form. Therefore, carbon was transformed by raising to the power of 2, new variable was $(\text{carbon})^2$. In the development of regression model, $(\text{carbon})^2$ was taken as an independent variable while HHV was a dependent variable. The value of r between $(\text{carbon})^2$ and HHV is 0.850 and $r^2$ is 0.722. From hypothesis test of the overall regression coefficient of quadratic model, it was found that p-value is less than 0.001. And hypothesis test of the individual of the regression coefficient indicates that p-value is also less than 0.001. Therefore, the developed model in quadratic form is as follows: HHV = 3,015.937 + 1.266 $(\text{carbon})^2$. However, this model did not meet the residual assumption requirements of the regression, thus this model cannot be accepted.

### *3.5 Comparison of measured HHV and predicted HHV*

Absolute percentage error (APE) and mean absolute percentage error (MAPE) of the developed models were calculated as follows:

$$\text{APE (\%)} = \left| \frac{\text{HHV}_\text{P} - \text{HHV}}{\text{HHV}} \right| \times 100$$

$$\text{MAPE (\%)} = \frac{1}{\text{N}} \sum \left| \frac{\text{HHV}_\text{P} - \text{HHV}}{\text{HHV}} \right| \times 100$$

where: HHV = measured HHV
$\text{HHV}_\text{P}$ = predicted HHV
N = number of samples

The absolute percentage error (APE) of the model based on physical composition, HHV = 5,383.541 + 0.457 $(\text{plastic})^2$, ranged from 0.04 to 13.52 % with the mean absolute percentage error (MAPE) of 3.41 %. And APE of the model based on ultimate analysis, HHV = 135.505 carbon, ranged from 0.29 to 23.79 % with the MAPE of 9.22 %, as shown in Table 2. It reveals that the model based on physical composition gives more accurate prediction of HHV of RDF than the model based on ultimate analysis. This may be due to the weight of sample used for the physical composition analysis is about 50 kg which should give more accurate and representative results than the ultimate analysis of only 1 mg sample.

**Table 2** Comparison of measured HHV and predicted HHV from the models based on physical composition and ultimate analysis

| Number of sample | Measured HHV (kcal/kg) | Physical composition model | | Ultimate analysis model | |
|---|---|---|---|---|---|
| | | Predicted HHV (kcal/kg) | APE (%) | Predicted HHV (kcal/kg) | APE (%) |
| 1 | 5811.4 | 5677.9 | 2.30 | 6318.6 | 8.73 |
| 2 | 6313.4 | 6316.0 | 0.04 | 7107.2 | 12.57 |
| 3 | 6237.6 | 6381.1 | 2.30 | 6680.4 | 7.10 |
| 4 | 6446.2 | 6464.3 | 0.28 | 7036.8 | 9.16 |
| 5 | 6496.8 | 6589.0 | 1.42 | 7088.3 | 9.10 |
| 6 | 7958.0 | 7424.6 | 6.70 | 7981.2 | 0.29 |
| 7 | 7437.2 | 7452.2 | 0.20 | 7960.9 | 7.04 |
| 8 | 7346.0 | 7086.3 | 3.54 | 7741.4 | 5.38 |
| 9 | 7674.9 | 7637.6 | 0.49 | 8110.0 | 5.67 |
| 10 | 6228.4 | 7070.7 | 13.52 | 7710.2 | 23.79 |
| 11 | 6503.9 | 7171.6 | 10.27 | 7778.0 | 19.59 |
| 12 | 7028.6 | 6934.7 | 1.34 | 7626.2 | 8.50 |
| 13 | 7463.3 | 7414.9 | 0.65 | 8004.3 | 7.25 |
| 14 | 7156.5 | 6821.3 | 4.68 | 7505.6 | 4.88 |
| Mean | | | 3.41 | | 9.22 |

## 4. Conclusions

To determine heating value of RDF, the models based on physical composition and ultimate analysis were developed in this study. The model based on physical composition, HHV = 5,383.541 + 0.457 $(\text{plastic})^2$, gives more accurate prediction of HHV of RDF than the model based on ultimate analysis, HHV = 135.505 carbon. However, it is recommended for further study that more samples should be collected in order to obtain more reliable mathematical models.

## 5. Acknowledgement

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