METHODS FOR DETERMINING CALORIFIC VALUES OF MUNICIPAL SOLID WASTE IN SALAYA SUBDISTRICT MUNICIPALITY

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METHODS FOR DETERMINING CALORIFIC VALUES OF MUNICIPAL SOLID WASTE IN SALAYA SUBDISTRICT MUNICIPALITY

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ABSTRACT

This research studied methods of determining the calorific values of municipal solid waste (MSW) from the Salaya Subdistrict Municipality, Nakorn Pathom Province. This research aimed to compare calorific values analyzed by using a bomb calorimeter with those predicted based on physical composition, proximate analysis and ultimate analysis based models including the Hess's law based model. Seven samples of solid waste were collected on 1 August 2011, 8, 11, 17, 23, 26 and 28 February 2012 in order to analyze physical composition, proximate analysis, ultimate analysis and calorific values.

The results showed that higher heating values (HHV) of combustible MSW ranged from 5,792 to 7,660 cal/g (dry basis) and an average value was 6,694 cal/g (dry basis). Compared to HHV predicted by the model based on physical composition: HHV (cal/g) = 5,383.541 + 0.457 $plastic^2$, which was Teerawattana et al' s equation, it was found that the HHV of combustible MSW was the most accurate with an average absolute error (AAE) of 3.33 %. Compared to HHV predicted by the model based on proximate analysis: HHV_{db} (MJ/kg) = 19.914 - ($0.2324ash_{db}$), which was Sheng and Azevedo's equation, it was found that HHV of wood was the most accurate with AAE of 2.02 %. Compared to HHV predicted by the model based on ultimate analysis: HHV_{ad} (cal/g) = $135.505C_{ad}$, which was Teerawattana et al' s equation, it was found that the HHV of plastic was the most accurate with AAE of 4.37 %. Compared to HHV predicted by the another model based on ultimate analysis: HHV_{db} (MJ/kg) = $-1.3675 + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$, which was Sheng and Azevedo's equation, it was found that the HHV of food waste, paper, wood and textile were accurate with AAE of 3.19, 1.48, 5.78 and 5.13 %, respectively. Compared to HHV predicted by the constructed model based on Hess's law, it was found that the HHV of plastic, wood, textile, and combustible MSW were rather accurate with AAE of 8.90, 7.22, 6.07 and 5.60 %, respectively. But the coefficient of determination (R^2) of the constructed equation was low, therefore further development should be conducted.

KEY WORDS: MUNICIPAL SOLID WASTE (MSW)/ HIGHER HEATING VALUE (HHV)/ PREDICTION/ COMBUSTIBLE MSW

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วิธีการหาค่าความร้อนของมูลฝอยจากเทศบาลตำบลศาลายา
METHODS FOR DETERMINING CALORIFIC VALUES OF MUNICIPAL SOLID WASTE
IN SALAYA SUBDISTRICT MUNICIPALITY

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บทคัดย่อ

งานวิจัยนี้ศึกษาวิธีการหาค่าความร้อนของมูลฝอยจากเทศบาลตำบลศาลายา จังหวัดนครปฐม มีวัตถุประสงค์เพื่อเปรียบเทียบวิธีการวิเคราะห์ค่าความร้อนโดยใช้ bomb calorimeter กับค่าที่ได้จากการทำนายโดยใช้สมการองค์ประกอบทางกายภาพ สมการผลการวิเคราะห์ proximate analysis และสมการผลการวิเคราะห์ ultimate analysis รวมถึงวิธีการคำนวณค่าความร้อนโดยอาศัยกฎของ Hess ซึ่งได้เก็บตัวอย่างมูลฝอย 7 ตัวอย่าง เมื่อวันที่ 1 สิงหาคม พ.ศ. 2554 8 11 17 23 26 และ28 กุมภาพันธ์ พ.ศ. 2555 มาทำการวิเคราะห์หาองค์ประกอบทางกายภาพ proximate analysis ultimate analysis และค่าความร้อน

ผลการวิจัยสามารถสรุปได้ดังนี้ higher heating value (HHV) ของมูลฝอยที่เผาไหม้ได้มีค่าอยู่ในช่วง 5,792 ถึง 7,660 cal/g (dry basis) และมีค่าเฉลี่ยเท่ากับ 6,694 cal/g (dry basis) และเมื่อเปรียบเทียบค่าความร้อนที่ได้จากการตรวจวัดกับค่าที่ทำนายได้ด้วยสมการองค์ประกอบทางกายภาพ: HHV (cal/g) = 5,383.541 + 0.457 $plastic^2$ ซึ่งเป็นสมการของ Teerawattana et al (2011) พบว่าสามารถทำนายค่าความร้อนของมูลฝอยที่เผาไหม้ได้แม่นยำที่สุด โดยมีค่า average absolute error (AAE) เท่ากับ 3.33 % เมื่อเปรียบเทียบค่าความร้อนที่ได้จากการตรวจวัดกับค่าที่ทำนายได้ด้วยสมการ proximate analysis: HHV_{db} (MJ/kg) = 19.914 - (0.2324ash_{db}) ซึ่งเป็นสมการของ Sheng and Azevedo (2005) พบว่าทำนายค่าความร้อนของมูลฝอยประเภทไม้ได้แม่นยำที่สุด โดยมีค่า AAE เท่ากับ 2.02 % เมื่อเปรียบเทียบค่าความร้อนที่ได้จากการตรวจวัดกับค่าที่ทำนายได้ด้วยสมการ ultimate analysis: HHV_{ad} (cal/g) = 135.505C_{ad} ซึ่งเป็นสมการของ Teerawattana et al (2011) พบว่าทำนายค่าความร้อนของมูลฝอยประเภทพลาสติกได้แม่นยำที่สุด โดยมีค่า AAE เท่ากับ 4.37 % ส่วนสมการ ultimate analysis: HHV_{db} (MJ/kg) = -1.3675 + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^* ซึ่งเป็นสมการของ Sheng and Azevedo (2005) สามารถทำนายค่าความร้อนของมูลฝอยประเภทเศษอาหาร กระดาษ ไม้ และผ้าได้แม่นยำ โดยมีค่า AAE เท่ากับ 3.19 1.48 5.78 และ 5.13 % ตามลำดับ และเมื่อเปรียบเทียบค่าความร้อนที่ได้จากการตรวจวัดกับค่าที่ทำนายได้ด้วยสมการที่สร้างขึ้นโดยอาศัยกฎของ Hess พบว่าสามารถทำนายค่าความร้อนของมูลฝอยประเภทพลาสติก ไม้ ผ้า และมูลฝอยที่เผาไหม้ได้ค่อนข้างแม่นยำ โดยมีค่า AAE เท่ากับ 8.90 7.22 6.07 และ 5.60 % ตามลำดับ แต่สมการที่สร้างขึ้นนี้มีค่าสัมประสิทธิ์การตัดสินใจ (R^2) ต่ำ ดังนั้นจึงควรพัฒนาสมการนี้ต่อไป

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CHAPTER I

INTRODUCTION

1.1 Background and significance of problems

Salaya Subdistrict Municipality is located in Nakhon Pathom Province which is in Bangkok Metropolitan Area. It is full of construction sites of apartments and housing developments. Increasing population leads to more municipal solid waste. According to civil registration, in March 2009, there were 11,813 persons living in Salaya Subdistrict Municipality and in February 2011 the number of people living in the Municipality increased to 12,167. Moreover, there are a wide range of educational institutions in Salaya Subdistrict Municipality such as Mahidol University, College of Dramatic Arts, Mahamakut Buddhist University, etc., resulting in a non-registered population of 20,000. Thirty-three tons per day of solid waste is delivered to the transfer station of Thipyawan International Co., Ltd., located in Thammasala Subdistrict, Nakornchaisri District, Nakhon Pathom Province. However, solid waste is still an issue especially in housing developments, commercial buildings and along Mahasawat Canal (Salaya Subdistrict Municipality, 2013: online). Therefore, it is necessary that Salaya Subdistrict Municipality had more effective solid waste management in compliance with the Tenth National Economic and Social Development Plan (2007 - 2011) emphasizing on increasing environmental management standards (Office of the Municipal Clerk of Salaya Subdistrict Municipality, 2013: online).

At the transfer station of Thipyawan International Co., Ltd., solid waste is sorted into main categories including plastic, metal, paper, etc., and sold as recycled materials. The remaining waste is transported to a Kamphaeng Saen landfill site in Nakhon Pathom Province. Solid waste landfills require a lot of land compared to solid waste incineration, which is a good alternative of solid waste management. Energy arising from solid waste incineration can also be recovered.

Data of calorific values of municipal solid waste are important for design and construction of incinerators. Previous researches created mathematic models to determine calorific values by using multiple linear regression analysis (Saenamnuayphol, 2004; Teerawattana et al, 2011; Kathiravale et al, 2003). In addition, calorific values of waste can be determined by using equations of Dulong and Shafizadeh (Menikpura and Basnayake, 2009), if the elemental composition is known.

This research studies determination of calorific values using a bomb calorimeter compared with calorific values calculated from equations of Teerawattana et al (2011) and Sheng and Azevedo (2005). Calorific value calculation according to the Hess's law was also studied.

1.2 Research objective

The main objective of this research was to compare calorific values of solid waste in Salaya Subdistrict Municipality determined by using bomb calorimeter with those determined by using physical composition, proximate analysis and ultimate analysis based models of Teerawattana et al (2011) and Sheng and Azevedo (2005) as well as those determined by using constructed Hess's law based model.

1.3 Research scope

1.3.1 Municipal solid wastes were sampling from collection vehicles of Salaya Subdistrict Municipality, Nakhon Pathom Province.

1.3.2 Physical composition of municipal solid waste in weight percentage of textile, food waste, wood, etc. was analyzed.

1.3.3 Proximate analysis (% moisture, % combustible matter and % ash) of each type of solid waste was conducted. Solid waste was dried at 107 ± 3 ^{o}C to determine % moisture (ASTM E 949 - 88) while % ash was determined from solid waste ignited at 575 ± 25 ^{o}C (ASTM E 830-87) and % combustible matter was calculated from 100 – (% moisture + % ash).

1.3.4 For ultimate analysis (C, H, N, O and S) of each type of solid waste, % carbon, % nitrogen and % sulfur were analyzed in a laboratory and % hydrogen and % oxygen were calculated from the H: O ratio obtained from Tchobanoglous et al (1993).

1.3.5 Calorific value of each type of solid waste was determined by using a bomb calorimeter.

1.3.6 Physical composition, proximate analysis, ultimate analysis based models of Teerawattana et al (2011) and Sheng and Azevedo (2005) were employed for prediction of calorific values in this study.

1.3.7 Hess's law based model was developed for prediction of calorific values.

1.4 Expected benefits

Alternative methods for determining calorific values with less time and expense consumption were expected.

CHAPTER II
LITERATURE REVIEW

This chapter is divided into seven sections.

2.1 Definition of solid waste

2.2 General information of Salaya Subdistrict Municipality

2.3 Type of refuse derived fuel (RDF)

2.4 Combustion

2.5 Heating value

2.6 Type of incinerators

2.7 Related researches

2.1 Definition of solid waste

Solid waste refers to paper, textile, food waste, product waste, materials, plastic bags, food containers, ash, excrement, carcass or other articles collected from roads, markets, animal houses or other places, as well as municipal infectious waste, toxic or hazardous waste (Public Health Act (No. 2) B.E. 2550 (2007): online).

Municipal solid waste (MSW) refers to any solid waste generated from community activities, e.g. residential households, commercial and business establishments, fresh market, institutional facilities and construction and demolition activities, excluding hazardous and infectious wastes (Pollution Control Department, 1998: online).

2.2 General information of Salaya Subdistrict Municipality

2.2.1 Location: Salaya Subdistrict Municipality is located 32 kilometers from Nakorn Pathom Province and 20 kilometers from Bangkok.

2.2.2 Total area: 13.5 square kilometers or 8,437.5 rais (Appendix A).

2.2.3 Boundary

North: Moo 5, Salaya Subdistrict, Putthamonthon District, SaiNoi District, Nonthaburi Province

South: Bang Toey Subdistrict, Bang Kra Tuek Subdistrict, Songkanong Subdistrict, Homgret Subdistrict, Samphan District, Nakorn Pathom Province

East: Saladang Subdistrict, Taweewattana District, Bangkok

West: Moo1 Salaya Subdistrict, Putthamonthon District

2.2.4 Weather: Three seasons with an average temperature of 31 degrees Celsius

2.2.5 Population: According to the population census of Putthamonthon District as of March 2009, there were 11,813 people living in Salaya Subdistrict Municipality, 5,265 of which were male and 6,548 of which were female and there were 4,072 households with an average density of 875 persons/square kilometer.

2.2.6 Economy

1) Agriculture: land is used mostly for farming of rice and crops such as mangoes, coconuts and grapefruit and livestock.

2) Commerce: there are approximately 200 restaurants and 150 shops.

3) Service: there are one hotel (Mahidol University), six banks, one gas station, one LPG station and no cinemas and entertainment places.

4) Labor: there are sufficient farmers, skilled workers, technicians and laborers.

5) Tourism and local knowledge sources: Putthamonthon, Krom Luang Chumphon Khet Udomsak Monument, Utthayan Road, Sirirukkachat Park, RuanThai, Arts Institute, Fine Arts Department, National Archives of Thailand and Ubonrangsi Chulamanee Foundation (Salaya Subdistrict Municipality, 2013: online).

2.3 Type of refuse derived fuel (RDF)

Refuse derived fuel (RDF) is fuel from solid waste categorized into seven groups according to ASTM E 856 - 83 (reapproved in 2004) as follows.

RDF 1: Wastes used in as - discarded form.

RDF 2: Wastes processed to coarse particle size with or without ferrous metal separation.

RDF 3: Shredded fuel derived from municipal solid waste (MSW) which has been processed to remove metal, glass, and other inorganic materials. This material has a particle size such that 95 weight % passes through a 2 in square mesh screen.

RDF 4: Combustible waste processed into powder form, 95 weight % passing 10 mesh screening.

RDF 5: Combustible waste identified (compressed) into the form of pellets, slugs, cubettes or briquettes.

RDF 6: Combustible waste processed into liquid fuels.

RDF 7: Combustible waste processed into gaseous fuel.

2.4 Combustion

2.4.1 Solid fuel combustion

In general, heated solid fuel evaporates or melts. There are five steps of solid waste combustion: oxygen reaching fuel’s surface, oxygen absorbed on fuel’s surface, absorbed oxygen reacting to fuel and getting product that is absorbed on fuel’s surface, product released from fuel’s surface and product spread from fuel’s surface. The step that occurs the last determines the combustion rate of each kind of solid waste (Jugjai, 2004).

2.4.2 Heat of reaction

Standard enthalpy change or heat of reaction is difference of enthalpy of products and enthalpy of reactants at standard state (25 ^{o}C and 1 atm. pressure). It is represented by ΔH^{o}. It can be written as Equation 2.1 or 2.2 (Jugjai, 2004 and Moore et al, 2008).

Heat of reaction = Heat of formation of products - Heat of formation of reactants.........(2.1)

$\Delta H° = \Sigma$ {(mole of product) × $\Delta H_f°$ (product)} - Σ {(mole of reactant) × $\Delta H_f°$ (reactant)}......(2.2)

When $\Delta H°$ is enthalpy of reaction at standard state; and

$\Delta H_f°$ is enthalpy at standard state per molecule.

2.4.3 Determination of heating values using Hess's law

Determination of heating values using Hess's law stating that enthalpy released from or absorbed into chemical reaction is always stable no matter at how many steps chemical reactions happened as long as the reactants and products do not change. This law is used to calculate heating values of complete combustion as shown in Equation 2.3.

$$\underbrace{C_uH_vO_wN_xS_y}_{\text{Fuel}} + \left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right) \underbrace{(O_2 + 3.75N_2)}_{\text{Air}} \rightarrow uCO_2 + \frac{v}{2}H_2O + ySO_2 + [3.75\left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right)]N_2 \quad \text{........ (2.3)}$$

Term –w/2 shows that oxygen in the fuel is used in combustion process. When u, v, w, x and y are the amount in mole of C, H, O, N and S, respectively (Jugjai, 2004). This equation is based on two assumptions: 1) 21 % of oxygen and 79 % of nitrogen in the air; and 2) the faction of the fuel that is ash is essentially inert to the combustion process (Strehlow, 1985).

2.5 Heating value

Heating values obtained from solid waste combustion is divided into two types. (ASTM E 711 - 87 and Moore et al, 2008)

2.5.1 Higher heating value (HHV)

Higher heating values obtained from solid waste combustion under standard state (at 25 ^{o}C and 1 atm. pressure) is analyzed in a laboratory by a bomb calorimeter. This HHV is the heating values released from a combustion theory while the water product is in liquid state.

2.5.2 Lower heating value (LHV)

LHV is heating value from normal combustion. Latent heat of vaporization is subtracted from HHV. Water product in normal combustion is in the gas state.

Apart from using a bomb calorimeter to determine heating values, physical composition, proximate analysis and ultimate analysis based equations derived from regression analysis can also be used to calculate heating values of solid waste as shown in Equations 2.4 - 2.23 in **Table 2.1**

Table 2.1 Equations for predicting heating values from related researches

Model	Type of models	Apply	Name	R^2	Units	Reference
Physical composition based models						
2.4	HHV_{db} = 5,441.4+33.10P_{db} - 80.45M	RDF (size25-100mm)	Chang et al	0.8692	cal/g	Chang et al, 1997
2.5	HHV_{db} = 6,295.7-64.05M	RDF (size >100mm)	Chang et al	0.7812	cal/g	Chang et al, 1997
2.6	LHV_{db}= 4,407.73 - 59.77M + 23.08P_{ar} + 6.63B_{ar}	MSW	Saenmnuayphol	0.8530	cal/g	Saenmnuayphol, 2004
2.7	HHV_{ad} = 5,383.541 + 0.457 P_{ad}^2	RDF	Teerawattana et al	0.726	cal/g	Teerawattana et al, 2011
Proximate analysis based models						
2.8	LHV_{db} = 71.98VS_{db}* - 797.77	MSW	Saenmnuayphol	0.8020	cal/g	Saenmnuayphol, 2004
2.9	HHV_{db} = 19.914 - (0.2324A_{db})	Biomass fuels	Sheng and Azevedo	0.6250	MJ/kg	Sheng and Azevedo, 2005
2.10	HHV_{db} = (-3.0368) + (0.2218VM_{db}) + (0.2601FC_{db})	Biomass fuels	Sheng and Azevedo	0.6170	MJ/kg	Sheng and Azevedo, 2005

Table 2.1 Equations for predicting heating values from related researches (cont.)

Model	Type of models	Apply	Name	R^2	Units	Reference
Ultimate analysis based models						
2.11	$HHV_{db} = 0.437\,C_{db} - 1.67$	Wood	Tillman	-	MJ/kg	Buckley and Domalski, 1988
2.12	$HHV_{db} = 0.3578\,C_{db} + 1.1357\,H_{db} + 0.059\,N_{db} + 0.1119\,S_{db} - 0.0845\,O_{db}$	Fossil fuels and terms for fuel nitrogen	Lloyd and Davenport	-	MJ/kg	Buckley and Domalski, 1988
2.13	$HHV_{db} = 0.3515\,C_{db} + 1.1617\,H_{db} + 0.06276\,N_{db} + 0.1046\,S_{db} - 0.1109\,O_{db}$	terms for fuel nitrogen	Boie	-	MJ/kg	Buckley and Domalski, 1988
2.14	$HHV_{db} = 0.3417\,C_{db} + 1.3221\,H_{db} + 0.1232\,S_{db} - 0.1198\,(O_{db} + N_{db}) - 0.0153\,A_{db}$	coal	The Institute of Gas Technology (IGT)	-	MJ/kg	Buckley and Domalski, 1988
2.15	$HHV_{db} = 81C_{db} + 342.5(H_{db} - 1/8O_{db}) + 22.5S_{db}$	-	Dulong	-	cal/g	Chang et al, 1997
2.16	$HHV_{db} = 81(C_{db} - 3/8O_{db}) + 171/8O_{db} + 342.5(H_{db} - 1/16O_{db}) + 25S_{db}$	-	Steuer	-	cal/g	Chang et al, 1997
2.17	$HHV_{db} = 81(C_{db} - 3/8O_{db}) + 342.5H_{db} + 22.55S_{db} + 171/4O_{db}$	-	Scheurer - Kestner	-	cal/g	Chang et al, 1997
2.18	$HHV_{db} = 10{,}938.01C_{db} + 78{,}808.25H_{db} + 4{,}701.54O_{db} - 615.10$	RDF (size25 - 100mm)	Chang et al	0.9250	cal/g	Chang et al, 1997
2.19	$HHV_{db} = 14{,}061.28C_{db} + 27{,}874.92H_{db} + 6{,}217.41O_{db} - 6{,}304.58$	RDF (size > 100mm)	Chang et al	0.9323	cal/g	Chang et al, 1997
2.20	$LHV_{db} = 1{,}076.71H_{db} + 233.27N_{db} - 21.60C_{db}$	MSW	Saenmnuayphol	0.8830	cal/g	Saenmnuayphol, 2004
2.21	$HHV_{db} = 0.3259C_{db} + 3.4597$	Biomass fuels	Sheng and Azevedo	0.7580	MJ/kg	Sheng and Azevedo, 2005
2.22	$HHV_{db} = (-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$	Biomass fuels	Sheng and Azevedo	0.8340	MJ/kg	Sheng and Azevedo, 2005
2.23	$HHV_{ad} = 135.505C_{ad}$	RDF	Teerawattana et al	0.716	cal/g	Teerawattana et al, 2011

Remark: db = dry basis, P = plastic, M = moisture content (% wet basis), ad = air dry basis, B = food waste and leave, VS* = volatile solids burn at 815 ^{o}C (%), A = ash (%),VM = volatile matter (%), FC = fixed carbon (%), C = carbon (%), H = hydrogen (%), N = nitrogen (%), S = sulfur (%), O = oxygen (%), and O^* = 100 - C - H - A

2.6 Type of incinerators

There are two main types of incinerators. The first one is a mass burning system that can burn many types of solid waste without pretreatment or with little pretreatment. Incinerators in this group include moving grate incinerators and rotary kiln incinerators. The second type can burn pretreated and homogenized waste including fluidized bed incinerators, which require pretreatment to make solid waste homogeneous.

All three types of incinerators can have energy recovery systems. Their effectiveness depends on their design and use. Characteristics, advantages and disadvantages of incinerators are as follows (The World Bank, 1999: online; Bontoux, 1999: online; Hulgaard and Vehlow, 2011).

2.6.1 Moving grate incinerator

After solid waste is fed into the hopper of a moving grate incinerator, it will be sent to a grate. A grate can move in the designed direction with air blowing from below and above so that solid waste is burnt evenly.

1) Advantages

1.1) Able to burn solid waste without sorting and size reduction

1.2) Able to design for solid waste with various components and heating values

1.3) 85 % thermal efficiency

2) Disadvantages

High investment and maintenance costs

2.6.2 Rotary kiln incinerator

A rotary kiln incinerator consists of an incline rotating cylinder so that solid waste can move along in the incinerator.

1) Advantages

1.1) Able to burn solid waste without sorting and size reduction

1.2) Able to design for solid waste with various components and heating values

1.3) 80 % thermal efficiency

2) Disadvantages

2.1) High investment and maintenance costs

2.2) Lower thermal efficiency than moving grate incinerators

2.6.3 Fluidized bed incinerator

A fluidized bed incinerator consists of a vertical refractory lined steel vessel and a bed of granular material such as silica sand, limestone, ceramic material, etc. There is fluidization with injection of air into the lower part of the incinerator stirring bed materials.

1) Advantages

1.1) Low investment and maintenance costs if it is a simple type

1.2) 90 % thermal efficiency

2) Disadvantages

Size and type of solid waste must always be controlled or pretreated beforehand.

2.7. Related researches

Buckley and Domalski (1988) estimated heating values of RDF 3 by collecting three times of samples. The first and second times, samples were prepared from the National Center for Resource Recovery (NCRR), Washington, D.C. The third time, samples were prepared from Americology (Division of American Can Co.), Milwaukee, Wisconsin. Chemical composition of the samples were analyzed and heating values were calculated by using equations of Dulong, Tillman, Lloyd and Davenport, Boie, and The Institute of Gas Technology (IGT), as shown in Equations 2.24 and 2.11 to 2.14.

Dulong Equation used for fossil fuel:

$$Q\ (MJ/kg) = 0.336\ C + 1.418\ H + 0.094\ S - 0.145\ O \quad (2.24)$$

Tillman Equation used for woods:

$$Q\ (MJ/kg) = 0.437\ C - 1.67 \quad (2.11)$$

Lloyd and Davenport Equation used for fossil fuel and terms for fuel nitrogen:

$$Q\ (MJ/kg) = 0.3578\ C + 1.1357\ H + 0.059\ N + 0.1119\ S - 0.0845\ O \quad (2.12)$$

Boie Equation used for terms for fuel nitrogen:

$$Q\ (MJ/kg) = 0.3515\ C + 1.1617\ H + 0.06276\ N + 0.1046\ S - 0.1109\ O \quad (2.13)$$

The Institute of Gas Technology (IGT) Equation used for coal:

$$Q\ (MJ/kg) = 0.3417\ C + 1.3221\ H + 0.1232\ S - 0.1198\ (0 + N) - 0.0153\ A \quad (2.14)$$

Dulong Equation and IGT Equation gave similar heating values of RDF 3 to those obtained from the experiment, with the error of 3%.

Chang et al (1997) estimated heating values of RDF 25 – 100 mm. and over 100 mm. in size in Tainan, Taiwan. Samples were collected more than ten times in July 1995 and March 1996. Chemical and physical compositions of the samples were analyzed and a regression analysis of RDF was conducted to find relationship between the composition and heating values of RDF of both sizes. Heating values were also estimated using equations of Dulong, Steuer, and Scheurer-Kestner as shown in Equations 2.15 to 2.17.

Dulong Equation:

$$HHV\ (cal/g) = 81C + 342.5(H - 1/8O) + 22.5S \quad (2.15)$$

Steuer Equation:

$$HHV\ (cal/g) = 81(C - 3/8O) + 171/8O + 342.5(H - 1/16O) + 25S \quad (2.16)$$

Scheurer-Kestner Equation:

$$HHV\ (cal/g) = 81(C - 3/8O) + 342.5H + 22.55S + 171/4O \quad (2.17)$$

When heating values determined from the bomb calorimeter and those calculated from regression Equations 2.4, 2.5, 2.18 and 2.19 were compared, it was found that both RDF 25 - 100 mm and over 100 mm in size gave percentage error at 0. Heating values calculated from equations of Dulong, Steuer, and Scheurer-Kestner had percentage error of RDF 25 – 100 mm. and over 100 mm. in size at -6.74, -0.76, 18.85 and -22.78, -17.69, -0.81, respectively. It was concluded that heating values calculated from the regression equations were close to those obtained from the experiment.

Physical composition based models

RDF (size25 - 100mm): HHV = 5441.4 + 33.10P - 80.45M……..…...(2.4)

RDF (size > 100mm): HHV = 6295.7 - 64.05M………………..…..(2.5)

Chemical analysis based models

RDF (size25 - 100mm): HHV = 10938.01C + 78808.25H + 4701.54O - 615.10...(2.18)

RDF (size > 100mm): HHV = 14061.28C + 27874.92H + 6217.41O - 6304.58....(2.19)

When

HHV = higher heating value (cal/g) C = carbon content (%)

P = plastic (%) H = hydrogen content (%)

M = moisture content (%) O = oxygen content (%)

Kathiravale et al (2003) estimated heating values of MSW in Kuala Lumpur, Malaysia, to identity the amount of energy that can be recovered and the amount of MSW used in combustion. Thirty samples were collected during March - August 2000. Physical composition was categorized into 12 types and heating value was determined by using a bomb calorimeter (Mahler Model T151D). Regression equations (2.25 - 2.30) were developed from physical composition, proximate analysis and ultimate analysis and heating values.

Physical composition based models

HHV = 112.517Ga - 183.6Pa + 288.737Pl + 5064.701………………....(2.25)

HHV = 81.209 Ga -285.035 Pl +8724.209…………………………....(2.26)

HHV = 112.815 Ga -184.366 Pa + 298.343 Pl - 1.920W + 5130.380…..(2.27)

Proximate analysis based models

HHV = 356.248VM - 6998.497……………………..…………………..(2.28)

HHV = 356.047VM - 118.035FC - 5600.613…………………………...(2.29)

Ultimate analysis based model

HHV = 416.638C - 570.017H - 259.031O + 598.955N - 5829.078…..…(2.30)

When

Q = net calorific value (kJ/kg)	VM = volatile matter (%)
Ga = garbage/food (%)	FC = fixed carbon (%)
Pa = paper (%)	C = carbon content (%)
Pl = plastic (%)	H = hydrogen content (%)
W = moisture content (%)	O = oxygen content (%)

The relationships between physical composition, proximate analysis and ultimate analysis and heating values of MSW were considered by regression analysis. It was found that physical composition based model, HHV = 112.517Ga - 183.6Pa + 288.737Pl + 5064.701, gave predicted heating values most similar to those measured by using a bomb calorimeter with the highest coefficient of determination (R^2 = 0.779). Moreover, proximate analysis based model, HHV = 356.248VM - 6998.497, and ultimate analysis based model, HHV = 416.638C - 570.017H-259.031O + 598.955N - 5829.078, gave predicted heating values close to those from the measurement.

Saenamnuayphol (2004) studied heating values of solid waste from On-nut Disposal Facility, Bangkok by using a multiple regression analysis. It was found that only 8.81 % of the average weight of solid waste was non-combustible because the waste was sorted beforehand. Most solid waste was organic. When combustible waste was considered, it was found that there were 44.08 % of food waste, 14.78 % of paper, 20.20 % of plastic, 0.90 % of leather and rubber, 3.46 % of textile, and 7.77 % of wood and leaves by wet weight. From regression analysis between heating values and physical composition, proximate analysis and ultimate analysis, Equations 2.6, 2.8 and 2.20 were developed.

Physical composition based model

$$LHV = 4407.73 - 59.77M + 23.08P + 6.63B \quad (2.6)$$

Proximate analysis based model

$$LHV = 71.98VS - 797.77 \quad (2.8)$$

Ultimate analysis based model

$$LHV = 1,076.71H + 233.27N - 21.60C \quad (2.20)$$

When

LHV = lower heating value (cal/g)
M = moisture content (%)
P = plastic (%)
B = food waste and leave (%)
VS = volatile solids (%)
H = hydrogen content (%)
N = nitrogen content (%)
C = carbon content (%)

It was also found that, the best equation was the physical composition based equation, LHV = 4,407.73 -59.77M + 23.08P + 6.63B. It gave the highest the coefficient of determination (R^2), 0.853 and could be practical. For proximate analysis based equation, LHV = 71.98VS - 797.77, only combustible MSW can be applied to this equation. The ultimate analysis based equation, LHV = 1,076.71H + 233.27N - 21.60C, shows that carbon increasing caused heating value decreasing which doesn't correspond with the truth.

Sheng and Azevedo (2005) studied heating values of 258 samples of biomass fuels from researches such as olive seeds, hay, oak sawdust, eucalyptus sawdust, almond shell, hazelnut shell, corncob, etc. Several equations were used to predict heating values of biomass fuels such as equations of Demirbas, Cordero et al, Channiwala and Parikh, and Jenkins. Moreover, basis of all samples were adjusted into dry basis before the regression analysis and results are shown in Equations 2.9, 2.10, 2.21 and 2.22.

Proximate analysis based models

$$HHV_{db} = 19.914 - (0.2324A_{db}) \quad (2.9)$$

$$HHV_{db} = (-3.0368) + (0.2218VM_{db}) + (0.2601FC_{db}) \quad (2.10)$$

Ultimate analysis based models

$$HHV_{db} = 0.3259C_{db} + 3.4597 \quad (2.21)$$

$$HHV_{db} = (-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*} \quad (2.22)$$

When

HHV = higher heating value (cal/g)
A = ash content (%)
VM = volatile matter (%)
FC = fixed carbon (%)
C = carbon content (%)
H = hydrogen content (%)
O^* = oxygen content (%)
$O^* = 100 - C - H - A$

The proximate analysis based model, $HHV_{db} = 19.914 - (0.2324A_{db})$, was more accurate in heating value prediction than another proximate analysis based model. While the ultimate analysis based model, $HHV_{db} = (-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$, was more accurate in heating value prediction than the proximate analysis based models.

Menikpura and Basnayake (2009) studied heating values of MSW in Kandy Municipality, Sri Lanka. Physical composition (food waste, plastic, wood, etc.) was analyzed, then dried at 105 ^{o}C for 24 hours and ground to pass through a 1-mm. sieve in order to determine heating values by using a bomb calorimeter.

Chemical composition was determined by two methods: 1) % C from volatile solids / 1.8 (for biodegradable materials), % H, % O, % N and % S calculated from chemical ratio according to Tchobanoglous et al (1993); and 2) data used in Tchobanoglous et al (1993). Chemical elements calculated from the first method, were substituted in equations of Dulong, Shafizadeh and Modified Shafizadeh. It was found that deviation between heating values of food waste predicted from those equations and those measured by using bomb calorimeter, were 1.43, 6.52 and 0.84 %, respectively.

When chemical elements from the second method were substituted in Dulong and Shafizadeh equations, it was found that deviation between heating values of wood predicted by both equations and those measured by using bomb calorimeter were 24.29 and 39.10 %, respectively. And when chemical elements from the two methods were used for predicting heating values by using Hess’s law, it was found that deviation between heating values of wood calculated by using Hess’s law and those measured by using bomb calorimeter, were -2.34 and 2.24 %, respectively. When deviation of heating values of wood predicted by using Hess’s law based equation, equations of Dulong, and Shafizadeh and those measured by the bomb calorimeter were compared, it was found that if chemical elements acquired from the second method were used, Hess law based equation, gave more accurate results than both equations of Dulong and Shafizadeh.

Teerawattana et al (2011) studied relationships between HHV and physical composition, proximate analysis and ultimate analysis of RDF, sorted from the On-nut Composting Plant, Bangkok. Fourteen samples were collected during June-November 2009. Then regression analysis was conducted to get Equations 2.7 and 2.23.

Physical composition based model

$$HHV_{ad} = 5,383.541 + 0.457P_{ad}^2 \qquad (2.7)$$

Ultimate analysis based model

$$HHV_{ad} = 135.505\ C_{ad} \qquad (2.23)$$

When

HHV = higher heating value (cal/g)

P = plastic (%)

C = carbon (%)

Physical composition based equation 2.7, $HHV_{ad} = 5,383.541 + 0.457P_{ad}^2$, was able to predict heating values more accurately compared to ultimate analysis based equation 2.23, $HHV_{ad} = 135.505\ C_{ad}$. The R^2 of Equations 2.7 and 2.23 were 0.726 and 0.716, respectively. Average absolute error (AAE) acquired from Equation 2.7 and 2.23 were 3.41 and 9.22 %, respectively.

Conclusion

Equations used for predicting heating values from relevant researches were selected for this study. It was found that equations from some researches were not able to predict heating values for the following reasons.

1. No clarity about the basis of analysis of heating values, physical composition, proximate analysis and ultimate analysis.

2. No clarity about types of heating values, HHV or LHV.

3. The equations used for predicting lower heating values (LHV) were not suitable for this study which predicted higher heating values (HHV).

Thus, the selected equations were divided by types of equations as follows.

1. Physical composition based model: used Equation 2.7, HHV_{ad} (cal/g) = $5,383.541 + 0.457\ P_{ad}^{\ 2}$, an equation of Teerawattana et al (2011).

2. Proximate analysis based model: used Equation 2.9, HHV_{db} (MJ/kg) = $19.914 - (0.2324A_{db})$, an equation of Sheng and Azevedo (2005).

3. Ultimate analysis based models: used Equation 2.21, HHV_{db} (MJ/kg) = $0.3259C_{db} + 3.4597$ and Equation 2.22, HHV_{db} (MJ/kg) = $(-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$, equations of Sheng and Azevedo (2005) and Equation 2.23, HHV_{ad} (cal/g) = $135.505C_{ad}$, an equation of Teerawattana et al (2011).

CHAPTER III
METHODOLOGY

There are six sections in this chapter as follows.

3.1 Research planning

3.2 Instruments and chemicals

3.3 Determination of sample size

3.4 Determination of solid waste composition

3.5 Determination of heating value of solid waste

3.6 Data analysis

3.1 Research planning

Planning of this research for comparison of heating values of solid waste in Salaya Subdistrict Municipality determined by using bomb calorimeter and those determined by using physical composition, proximate analysis, and ultimate analysis based models as well as those determined by using developed Hess's law based model are shown in **Figure 3.1**.

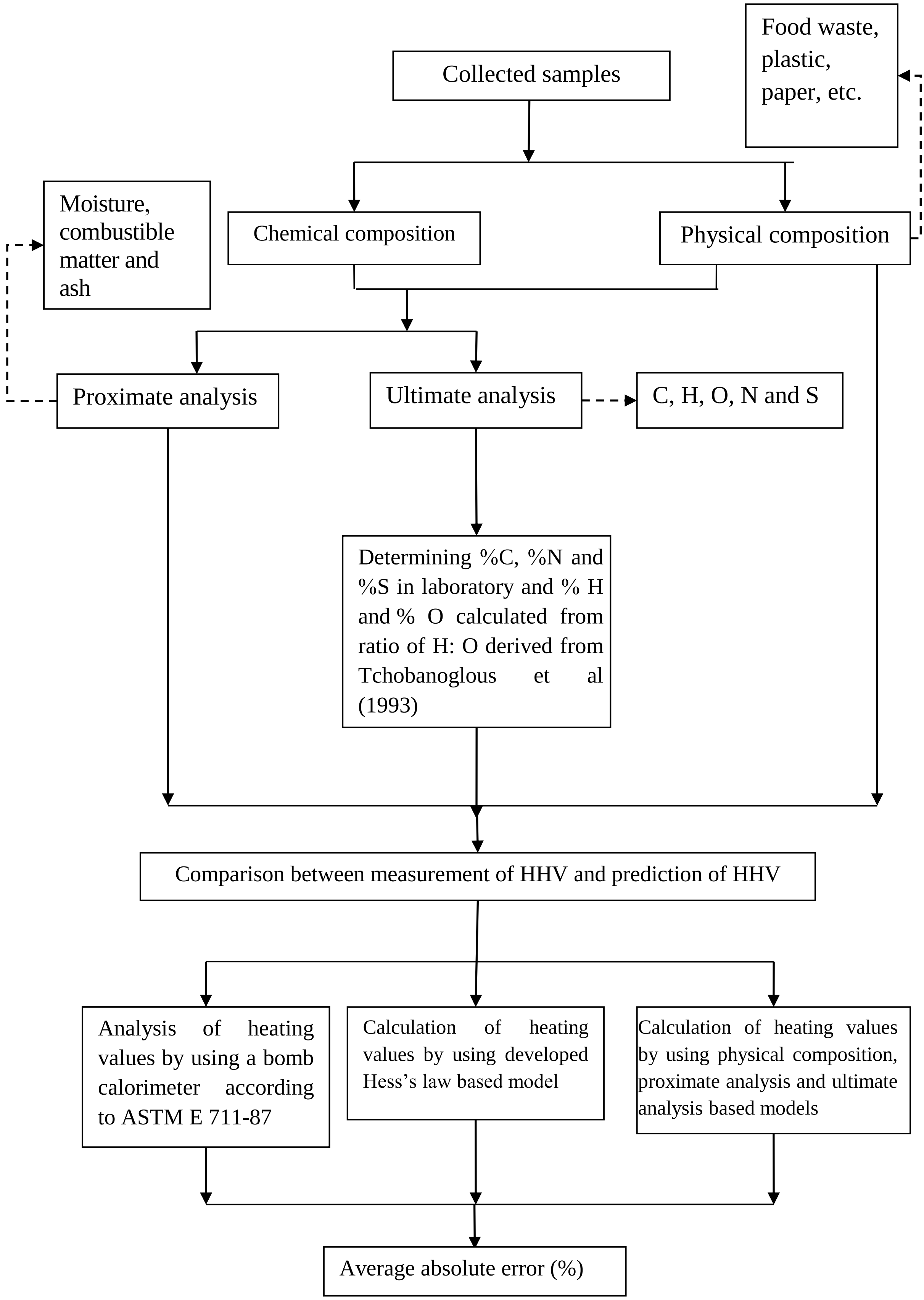

Figure 3.1 Flow chart of research plan

3.2 Instruments and chemicals

3.2.1 Instruments

1) Analytical balance (Mettler toledo, XS 204)
2) Drying oven (Memmert, UNB 300)
3) Desiccator
4) Muffle furnace (Carbolite, CWF 1100)
5) Oxygen bomb calorimeter (Parr, 6200)
6) Fume hood
7) Hotplate (Labinco, L39)
8) pH meter (Orion, EA 940)
9) Block digestion unit (Foss, 2020)
10) Distillation unit (Foss, Kjeltec 8100)
11) Carbon analyzer (Analytik jena, Multi N/C 2100/2100S)
12) Distilled water
13) Qualitative filter paper (Whatman, No. 5)
14) Ashless filter paper (Whatman, No. 42)

3.2.2 Chemicals

1) Benzoic acid, C_6H_5COOH (analytical grade, Parr)
2) Oxygen gas 99.50 %
3) Methyl red (analytical grade, Panreac)
4) Bromcresol green (analytical grade, Ajax)
5) 95 % Ethyl alcohol
6) Sodium carbonate, Na_2CO_3 (analytical grade, Univar)
7) Ammonium hydroxide, NH_4OH (analytical grade, Mallinckrodt)
8) Bromine (analytical grade, Riedel - dettaen)
9) 37 % Hydrochloric acid, HCl (analytical grade, Merck)
10) Sodium hydroxide, NaOH (analytical grade, Merck)
11) Barium chloride, $BaCl_2$ (analytical grade, Univar)
12) 65 % Nitric acid, HNO_3 (analytical grade, Merck)
13) Silver nitrate, $AgNO_3$ (analytical grade, Fisher scientific)

14) 95 - 97 % Sulfuric acid, H_2SO_4 (analytical grade, Merck)

15) Sucrose, $C_{12}H_{22}O_{11}$ (analytical grade, Univar)

16) Potassium sulfate, K_2SO_4 (analytical grade, Univar)

17) Mercury sulfate, $HgSO_4$ (analytical grade, Univar)

18) Selenium, Se (analytical grade, Univar)

19) Potassium sulfide, K_2S (laboratory grade, Ajax)

20) Boric acid, H_3BO_3 (analytical grade, Merck)

21) Methylene blue (analytical grade, Univar)

22) Calcium carbonate, $CaCO_3$ (analytical grade, Univar)

3.3 Determination of sample size

The sample size of solid waste was calculated by using Equation 3.1 (Vanichbuncha, 2008)

$$n = \frac{Z^2 \times \sigma^2}{e^2} \quad \text{......(3.1)}$$

Where: n = sample size

Z = values of standard distribution (confidence level = 95 %; Z = 1.96)

σ^2 = variance of population

e = predetermined maximum error

Variance of the sample group (S^2), 88506 cal/g, calculated from the maximum and the minimum heating values acquired from the research of Saenamnuayphol (2004) was used instead of variance of the population (σ^2). The calculated sample size was equal to 34 (details are in Appendix B). However, due to expenses and time constraints, seven samples were collected. Each sample was taken each day (Monday - Sunday) from a collection truck unloading at the transfer station as shown in **Table 3.1**.

Table 3.1 Plan of collecting solid waste samples from collection trucks at transfer station.

Sampling date	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
	1/8/11	28/2/12	8/2/12	23/2/12	17/2/12	11/2/12	26/2/12
collection truck no.	1	2	4	5	3	3	1

3.4 Determination of solid waste composition

3.4.1 Determination of physical composition

In the solid waste sample collection for determination of physical composition, approximately 400 kg of solid waste was sampling from a collection truck unloading at transfer station. After quartering process, approximately 100 kg of solid waste sample was taken for physical composition (food waste, plastic, paper, etc.) analysis, as % wet weight, according to ASTM D 5231 – 92.

3.4.2 Determination of proximate analysis and ultimate analysis

1) Step of sample preparation

Sampling each type of solid waste for approximately 2 – 4 kg by quartering technique for proximate analysis and ultimate analysis was conducted according to ASTM D 5115 - 90 (Reapproved 2004). These samples, which were called gross sample were kept in sealed plastic bags.

After that, each gross sample was quartering to get not exceed 2 kg. sample which was called laboratory sample. These samples were dried at 40 ^{o}C until they reached constant weight. The initial weight and final weight were recorded to determine air dry moisture (%) of each type of solid waste. Then, the particle size of waste was reduced to around 0.5 mm. by knife, hammer, mortar, pruning shears, scissors, paper cutter and/or mill. These samples were quartering to get approximately 50 g samples, which were called analysis samples, according to ASTM E 829 – 94. These samples were kept in sealed plastic bags for proximate analysis (moisture content, ash and combustible matter). After that, the ground air-dried samples were dried at 107 ^{o}C for ultimate analysis (carbon, hydrogen, oxygen, nitrogen and sulfur) and higher heating value (HHV) analysis.

2) Determination of proximate analysis

2.1) Total moisture means air dry moisture and residual moisture. Air dry moisture was determined in the sample preparation step. Air-dried samples were then dried at 107 ± 3 ^{o}C to determine residual moisture in % by weight according to ASTM E 949 - 88 (Reapproved 2004).

2.2) Ash means solid residue remaining in % by weight after burning at 575 ± 25 ^{o}C. The procedure was analyzed according to ASTM E 830 - 87 (Reapproved 2004).

2.3) Combustible matter means the sum of fixed carbon and volatile solids, calculated from 100 - (% moisture + % ash).

3) Determination of ultimate analysis

3.1) Carbon means elemental carbon in solid waste expressed in percentage by weight. Ground dried samples were analyzed by a carbon analyzer (Analytik jena, Multi N/C 2100/2100S).

3.2) Nitrogen means the amount of nitrogen content in the form of ammonia-nitrogen or organic-nitrogen. Ground dried samples were analyzed according to ASTM E 778 - 87 (Reapproved 2004).

3.3) Sulfur means the amount of sulfur in the sulfur and sulfate. Ground dried samples were analyzed by a bomb washing method according to ASTM E 775 - 87 (Reapproved 2004). Sulfur in bomb washing was precipitated as $BaSO_4$. Precipitate was then filtered, ashed and weighed.

3.4) Hydrogen and oxygen means hydrogen and oxygen in solid waste expressed in percentage by weight. Hydrogen and oxygen were calculated from 100 - (% C + % N + % S + % Ash), and the ratio of H: O from Tchobanoglous et al (1993).

3.5 Determination of heating values of solid waste

This research determined heating values of solid waste as follows.

3.5.1 Analysis of heating values according to ASTM E 711-87

An analyzing method according to ASTM E 711-87 (Reapproved 2004) was used for determining heating value by a bomb calorimeter. Approximately 1 gram of ground dried sample (analysis sample) was ignited in a bomb calorimeter. Then calorific values were calculated according to Equations 3.2 and 3.3.

Calculation of gross calorific value

$H_s = [(T)(E) - e_1 - e_2 - e_3]/g$ ……………………………………………(3.2)

When H_s = gross calorific value, J/g

T = corrected temperature rise, ^oC

E = energy equivalent, J/^oC

g = weight of sample, g

e_1 = correction for the heat of formation of HNO_3, J

= 20 × each milliliter of standard alkali titrant

e_2 = correction for heat of formation of H_2SO_4, J

= 55.2 × percent of sulfur in sample × weight of sample, g

e_3 = correction for heat of combustion of firing wire, J.

= 9.63 × combusted firing wire (cm.), J

Calculation of net heat of combustion

$H_i = H_s - 23.96(H \times 9)$ ………………………………………………(3.3)

When H_i = net calorific value (net heat of combustion), J/g

H_s = gross calorific value (gross heat of combustion), J/g

H = total hydrogen, % (dry basis)

3.5.2 Determination of heating value by using Hess's law

According to the Hess's law, Equation 2.1 is written as follows.

Heat of reaction = Heat of formation of products - Heat of formation of reactants..(2.1)

Steps in calculating heating values by using Hess's law were as follows:

1) Used ultimate analysis data, changed basis from dry basis to dry and ash free basis and divided by atomic weight. Then adjusted carbon atom into full number to get chemical formulae of each type of solid waste and combustible MSW.

2) Calculated molecular weight of each type of solid waste and combustible MSW

3) Chemical formulae of each type of solid waste and combustible MSW were substituted in complete combustion Equation 2.3.

$$C_uH_vO_wN_xS_y + \left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right)(O_2 + 3.75N_2)$$

$$\rightarrow uCO_2 + \frac{v}{2}H_2O + ySO_2 + [3.75\left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right) + \frac{x}{2}]N_2 \quad \text{..........(2.3)}$$

4) Calculated heat of formation of products from complete combustion equation by using Equations 3.4 or 3.5

Heat of formation of products = Σ {(mole of product) × Δ $H_f°$ (product)}............ (3.4)

Or

Heat of formation of products = moles of CO_2 × Δ $H_f°$ $(CO_2)_{(g)}$ + moles of H_2O × Δ $H_f°$ $(H_2O)_{(l)}$ + moles of SO_2 × Δ $H_f°$ $(SO_2)_{(g)}$…………...………………...(3.5)

When Δ H_f^o of $CO_{2\,(g)}$, $H_2O_{(l)}$ and $SO_{2\,(g)}$ are as follows.

$C_{(s)} + O_{2\,(g)} \rightarrow CO_{2\,(g)}$ ΔH_f^o of $CO_{2\,(g)}$ = -94.01 kcal/mole………...……(3.6)

$H_{(g)} + ½\, O_{2\,(g)} \rightarrow H_2O_{(l)}$ ΔH_f^o of $H_2O_{(l)}$ = -68.28 kcal/mole……….………(3.7)

$S_{(s)} + O_{2\,(g)} \rightarrow SO_{2\,(g)}$ ΔH_f^o of $SO_{2\,(g)}$ = -70.91 kcal/mole……….…...…(3.8)

5) Changed the unit of heat of reaction, which was heating value determined from a bomb calorimeter, from cal/g to kcal/mole.

6) Developed a regression equation between heat of formation of products and heat of reaction for predicting heating values from heat of formation of products.

3.5.3 Calculation of heating values from physical composition, proximate analysis and ultimate analysis based models

For physical composition based model, Equation 2.7: HHV_{ad} (cal/g) = 5,383.541 + 0.457 $P_{ad}{}^2$, which was the equation of Teerawattana et al (2011) was used.

For proximate analysis based model, Equation 2.9: HHV_{db} (MJ/kg) = 19.914 - (0.2324A_{db}), which was the equation of Sheng and Azevedo (2005) was used.

For ultimate analysis based models, Equation 2.21: HHV_{db} (MJ/kg) = 0.3259C_{db} + 3.4597 and Equation 2.22: HHV_{db} (MJ/kg) = (-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^*, which were the equations of Sheng and Azevedo (2005) and equation 2.23: HHV_{ad} (cal/g) = $135.505C_{ad}$, which was the equation of Teerawattana et al (2011) were used.

3.6 Data analysis

In data analysis of each type of solid waste and combustible MSW, statistics such as average, standard deviation, absolute error (AE) and average absolute error (AAE) were used as shown in Equations 3.9 - 3.12 (Vanichbuncha, 2008; Sheng and Azevedo, 2005). Relationship between heat of formation of products and heat of reaction was analyzed by using simple linear regression as shown in Equations 3.13 - 3.15.

$$\text{Average, } \overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad \text{...(3.9)}$$

$$\text{Standard deviation, } S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} \quad \text{...(3.10)}$$

$$\text{Absolute error, } AE\ (\%) = \left|\frac{\text{calculated value} - \text{measured value}}{\text{measured value}}\right| \times 100 \quad \text{...(3.11)}$$

$$\text{Average absolute error, } AAE\ (\%) = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\text{Calculated value} - \text{Measured value}}{\text{Measured value}}\right| \times 100 \quad \text{...(3.12)}$$

When $\overline{X}$ = average of the sample

X_i = data of the sample

n = total data

S = standard deviation

AE (%) = absolute error

AAE (%) = average absolute error

$$Y = \beta_0 + \beta_1 X \quad \text{...(3.13)}$$

$$\beta_0 = \frac{\sum_{i=1}^{n} Y_i}{n} - \beta_1 \frac{\sum_{i=1}^{n} X_i}{n} \quad \text{...(3.14)}$$

$$\beta_1 = \frac{\left(\sum_{i=1}^{n} X_i Y_i - \frac{\sum_{i=1}^{n} X_i Y_i}{n}\right)}{\sum_{i=1}^{n} {X_i}^2 - \frac{\sum_{i=1}^{n} {X_i}^2}{n}} \quad \text{...(3.15)}$$

When Y = heat of reaction

β_0 = y - axis intercept

β_1 = regression coefficients

X = heat of formation of products

Y_i = data of heat of reaction

n = total data of the sample

X_i = data of the heat of formation of products

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Determination of solid waste composition

Seven samples were collected to study physical composition, proximate analysis, ultimate analysis and heating values of municipal solid waste. Study results are as follows. (Details are shown in Appendix C)

4.1 1. Determination of physical composition

Physical composition of seven samples of municipal solid waste in Salaya Subdistrict Municipality was determined. It was found that the average values of solid waste components, namely food waste, plastic, paper, wood, textile, rubber, foam, glass, metal, rubble, hazardous waste and miscellaneous were 58.55, 24.95, 4.56, 1.66, 1.13, 1.14, 1.75, 3.34, 0.58, 0.75, 0.09 and 1.51 % in wet weight, respectively, as shown in **Table 4.1**. The average value of combustible solid waste (food waste, plastic, paper, wood, textile, rubber and foam) was 93.74 % and that of non-combustible solid waste (glass, metal, rubble, hazardous waste and miscellaneous) was 6.27 %. Compared to physical composition of municipal solid waste in 27 districts in Bangkok collected from On-nut Disposal Facility by Saenamnuayphol (2004), the average values of solid waste components, namely food waste, plastic, paper, wood and leaves, textile, leather and rubber, glass, metal, stone and ceramic, hazardous waste, and miscellaneous were 44.08, 20.20, 14.78, 7.77, 3.46, 0.90, 3.33, 1.34, 2.33, 0.21 and 1.60 %, respectively. Plastic, leather and rubber, glass and miscellaneous in municipal solid waste from Bangkok were close to those from Salaya Subdistrict Municipality. Average value of combustible solid waste (food waste, plastic, paper, wood and leaves, textile and rubber) in Bangkok was 91.19 % and the average value of non-combustible solid waste (glass, metal, stone and ceramic, hazardous waste and miscellaneous) was 8.81 % which were close to municipal solid waste of Salaya Subdistrict Municipality. Compared to municipal solid waste in Kuala Lumpur, Malaysia studied by Kathiravale et al (2003), physical composition, namely organics/food waste, plastic, paper, wood, textile, rubber, yard waste, glass, aluminum, ferrous and fine (20mm. sieve) were 51.94, 20.97, 11.23, 1.80, 1.58, 0.68, 4.50, 2.54, 0.24, 2.28 and 2.24 % (as received basis), respectively. The average values of food waste, plastic, wood, and textile were close to those of solid waste components from Salaya Subdistrict Municipality.

Table 4.1 Physical composition of municipal solid waste in Salaya Subdistrict Municipality on 1 August 2011 and 8, 11, 17, 23, 26 and 28 February 2012 (as received basis)

Components	Range % by weight*	Mean % by weight* (n = 7)	SD*	Range % by weight**	Mean % by weight** (n = 60)	SD**
Food waste	49.49 - 67.65	58.55	6.10	21.83 - 63.31	44.08	8.87
Plastic	15.39 - 31.79	24.95	6.37	12.86 - 31.28	20.20	3.86
Paper	3.23 - 7.10	4.56	1.32	6.01 - 37.39	14.78	6.13
Wood	0.54 - 2.94	1.66	0.93	0.67 - 27.07[a]	7.77[a]	5.23[a]
Textile	0.00 - 2.15	1.13	0.87	0.00 - 11.88	3.46	3.02
Rubber	0.00 - 3.91	1.14	1.41	0.00 - 7.98[b]	0.90[b]	1.53[b]
Foam	0.49 - 2.69	1.75	0.79	-	-	-
Glass	1.33 - 4.89	3.34	1.30	0.00 - 17.01	3.33	3.07
Metal	0.00 - 1.01	0.58	0.41	0.20 - 4.02	1.34	0.88
Rubble	0.00 - 3.32	0.75	1.35	0.00 - 9.05[c]	2.33[c]	1.97[c]
Hazardous waste	0.00 - 0.54[d]	0.09[d]	0.20[d]	0.00 - 1.78	0.21	0.32
Miscellaneous	0.00 - 4.41[e]	1.51[e]	1.51[e]	0.00 - 8.89	1.60	2.38
Total		**100**			**100**	

Remark: * = this research

** = Saenamnuayphol, 2004

a = wood and leaves

b = leather and rubber

c = stone and ceramic

d = light bulb

e = sanitary napkin diaper and hypodermic syringe

In analysis of physical composition of solid waste, foam was separately considered from other kinds of plastic because proximate analysis, ultimate analysis and determination of heating values of foam were not conducted.

In consideration of physical composition (air dry basis) of combustible municipal solid waste (MSW) in Salaya Subdistrict Municipality, it was found that food waste, plastic, paper, wood, textile and rubber were in the range of 25.57 - 70.11, 20.62 - 54.24, 4.45 - 11.64, 0.98 - 7.41, 0.00 - 3.49 and 0.00 - 10.50 % (air dry basis), respectively. The average values of food waste, plastic, paper, wood, textile and rubber were 43.01, 40.40, 8.19, 3.50, 1.97 and 2.92 % (air dry basis), respectively, as shown in **Table 4.2**. When comparing results of this study with the research of Teerawattana (2010), who analyzed physical composition of RDF from On-nut Composting Plant, it was found that the average values of wood and textile were 3.21 and 1.94 % (air dry basis), respectively, which were similar to those of this study. Whereas the average values of food waste, plastic, paper and rubber, were 6.02, 56.04, 0.40 and 0.39 % (air dry basis), respectively, which were quite different from those of this study because the samples of Teerawattana (2010) were the remains from screening and sorting of solid waste in the municipal solid waste composting process.

Table 4.2 Physical composition of combustible MSW in Salaya Subdistrict Municipality on 1 August 2011 and 8, 11, 17, 23, 26 and 28 February 2012 (air dry basis)

Components	Range*	Mean* (n = 7)	SD*	Range**	Mean** (n = 15)	SD**
Food waste	25.57 - 70.11	43.01	14.32	0.12 - 13.63	6.02	4.69
Plastic	20.62 - 54.24	40.40	12.98	25.38 - 70.23	56.04	11.59
Paper	4.45 - 11.64	8.19	2.60	0.00 - 4.36	0.40	1.13
Wood	0.98 - 7.41	3.50	2.31	0.00 - 11.49	3.21	3.43
Textile	0.00 - 3.49	1.97	1.52	0.00 - 12.19	1.94	3.44
Rubber	0.00 - 10.50	2.92	3.73	0.00 - 5.83	0.39	1.51
Compost				19.01 - 47.84	31.77	7.02
Leather				0.00 - 3.38	0.23	0.87
Total		100			100	

Remark: * = this research

** = Teerawattana, 2010

When considering physical composition (dry basis) of combustible MSW in Salaya Subdistrict Municipality, it was found that food waste, plastic, paper, wood, textile and rubber were in the range of 23.99 - 68.52, 22.13 - 56.68, 4.34 - 11.69, 0.94 - 7.15, 0.00 - 3.46 and 0.00 - 11.26 % (dry basis), respectively. The average values of food waste, plastic, paper, wood, textile and rubber were 41.11, 42.26, 8.14, 3.41, 1.98

and 3.10 % (dry basis), respectively, as shown in **Table 4.3**. When physical components of combustible MSW in this study were compared with those of Chang et al (1997) study of RDF in Taiwan, it was found that the average values of food waste, plastic, paper, garden trimmings, textile and leather/rubber in RDF were 16.99, 31.86, 34.63, 4.90, 10.93 and 0.70 % (dry basis), respectively. It can be seen that wood had the close value while food waste, plastic, paper, textile and rubber were quite different.

Table 4.3 Physical composition of combustible MSW in Salaya Subdistrict Municipality on 1 August 2011 and 8, 11, 17, 23, 26 and 28 February 2012 (dry basis)

Components	Range*	Mean* (n = 7)	SD*	Mean** (n = 13)
Food waste	23.99 - 68.52	41.11	14.33	16.99
Plastic	22.13 - 56.68	42.26	13.14	31.86
Paper	4.34 - 11.69	8.14	2.60	34.63
Wood	0.94 - 7.15	3.41	2.24	4.90[a]
Textile	0.00 - 3.46	1.98	1.53	10.93
Rubber	0.00 - 11.26	3.10	3.99	0.70[b]
Total		100		100

Remark: * = this research

** = modified Chang et al, 1997

a = garden trimmings

b = leather/rubber

4.1.2. Determination of proximate analysis

Proximate analysis (as received basis) of each type of solid waste including moisture content, combustible matter and ash were analyzed. It was found that the average value of total moisture of food waste was the highest, 76.08 %, followed by plastic 40.84 % and paper 37.83 %. The average values of combustible matter of wood and rubber were the highest, 68.47 and 67.36 %, respectively. The average value of ash content of rubber was found the highest, 26.13 % (as received basis) due to high amount of non-combustible matter. When considering proximate analysis (as received basis) of combustible MSW from Salaya Subdistrict Municipality, it was found that the average values of total moisture, combustible matter and ash were 61.84, 34.90 and 3.25 %, respectively, as shown in **Table**

4.4.When comparing the results of this study with Chang et al (1997) study, the average values of total moisture and ash of RDF in Taiwan were 50.65 and 12.21 % (as received basis), respectively, which were different, whereas the average value of combustible matter was 37.15 %, which was not different.

Table 4.4 Proximate analysis (as received basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Range of total moisture (% ar)	Mean ± SD of total moisture (% ar)	Range of combustible matter (% ar)	Mean ± SD of combustible matter (% ar)	Range of ash (% ar)	Mean ± SD of ash (% ar)
Food waste	69.84 - 82.64	76.08 ± 5.14	15.64 - 27.04	21.35 ± 4.43	0.82 - 5.97	2.57 ± 1.90
Plastic	25.77 - 59.20	40.84 ± 11.57	40.18 - 72.93	56.29 ± 11.77	0.62 - 4.83	2.87 ± 1.66
Paper	20.43 - 53.02	37.83 ± 11.16	39.44 - 61.08	52.19 ± 9.80	2.55 - 21.58	9.98 ± 6.10
Wood	12.88 - 58.71	29.34 ± 16.11	40.36 - 85.41	68.47 ± 15.26	0.93 - 5.44	2.19 ± 1.52
Textile	18.30 - 49.07	36.28 ± 11.39	47.44 - 79.89	60.76 ± 11.97	1.21 - 6.74	2.96 ± 2.29
Rubber	2.21 - 11.33	6.52 ± 3.52	55.72 - 85.16	67.36 ± 11.43	12.63 - 37.68	26.13 ± 9.56
Combustible MSW	55.13 - 68.09	61.84 ± 4.58	30.16 - 40.24	34.90 ± 3.61	1.70 - 5.41	3.25 ± 1.48

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood, textile and rubber

ar = as received basis

When considering proximate analysis (air dry basis) of each type of solid waste, it was found that the average value of residual moisture of food waste was the highest, 10.09 %, followed by wood and paper, 8.18 and 6.16 %, respectively. The average value of residual moisture of rubber was the least, 0.46 %. The average value of combustible matter (air dry basis) of plastic was the highest, 94.23 %, followed by textile, wood and food waste, 90.71, 89.09 and 80.51 %, respectively. Rubber has the highest ash content with the average value of 27.96 %, followed by paper, 14.97 %, and plastic and textile, 4.91 and 4.53 % (air dry basis), respectively. The average values of residual moisture, combustible matter and ash of combustible MSW in Salaya Subdistrict Municipality were 5.55, 86.55 and 7.89 % (air dry basis), respectively, as shown in **Table 4.5**. When comparing results of this study with Teerawattana (2010) study, residual moisture and ash of RDF from On-nut Composting Plant, Bangkok were 2.93 and 25.27 % (air dry basis), respectively, which were quite different, whereas combustible matter was 71.80 % (air dry basis), which was not much different.

Table 4.5 Proximate analysis (air dry basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Range of residual moisture (% ad)	Mean ± SD of residual moisture (% ad)	Range of combustible matter (% ad)	Mean ± SD of combustible matter (% ad)	Range of ash (% ad)	Mean ± SD of ash (% ad)
Food waste	7.98 - 12.20	10.09 ± 1.74	71.68 - 85.31	80.51 ± 4.59	2.90 - 20.30	9.40 ± 5.85
Plastic	0.44 - 1.74	0.86 ± 0.45	89.79 - 98.04	94.23 ± 3.23	1.52 - 8.47	4.91 ± 3.00
Paper	4.97 - 7.20	6.16 ± 0.76	68.92 - 89.54	78.86 ± 7.19	3.83 - 25.65	14.97 ± 7.84
Wood	7.25 - 9.26	8.18 ± 0.76	85.29 - 90.74	89.09 ± 1.93	1.76 - 5.83	2.73 ± 1.44
Textile	2.12 - 7.90	4.75 ± 2.32	82.46 - 96.02	90.71 ± 5.57	1.86 - 9.64	4.53 ± 3.41
Rubber	0.12 - 0.82	0.46 ± 0.25	59.40 - 86.75	71.58 ± 10.44	12.87 - 40.16	27.96 ± 10.41
Combustible MSW	4.14 - 7.23	5.55 ± 1.38	83.44 - 90.69	86.55 ± 2.40	4.23 - 12.08	7.89 ± 3.02

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood, textile and rubber

ad = air dry basis

From the calculation of proximate analysis (dry basis) of each type of solid waste, it was found that the average value of combustible matter of wood was the highest, 97.02 %, followed by textile, 95.18 %. Rubber had the least combustible matter, 71.90 %. It was also found that the average value of ash of rubber was the highest, 28.10 %, followed by paper and food waste, 15.91 and 10.38 % (dry basis), respectively. For combustible MSW, it was found that the average values of combustible matter and ash were 91.66 and 8.34 % (dry basis), respectively, as shown in **Table 4.6**.

Table 4.6 Proximate analysis (dry basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Range of combustible matter (% db)	Mean ± SD of combustible matter (% db)	Range of ash (% db)	Mean ± SD of ash (% db)
Food waste	77.93 - 96.69	89.62 ± 6.28	3.31 - 22.07	10.38 ± 6.28
Plastic	91.38 - 98.47	95.04 ± 3.04	1.53 - 8.62	4.96 ± 3.04
Paper	72.88 - 95.90	84.09 ± 8.21	4.10 - 27.12	15.91 ± 8.21
Wood	93.60 - 98.08	97.02 ± 1.59	1.92 - 6.40	2.98 ± 1.59
Textile	89.53 - 98.10	95.18 ± 3.74	1.90 - 10.47	4.82 ± 3.74
Rubber	59.66 - 87.08	71.90 ± 10.47	12.92 - 40.34	28.10 ± 10.47
Combustible MSW	87.35 - 95.54	91.66 ± 3.12	4.46 - 12.64	8.34 ± 3.12

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood, textile and rubber

db = dry basis

4.1.3. Determination of ultimate analysis

In determination of heating value and sulfur of rubber, it was found that rubber release plentiful heating value, which might melt the platinum electrode in bomb. It was also found that there were brown traces in the bomb making it difficult to notice a change in color of the wash solution in the bomb from light blue to light orange. This is a step in sulfur analysis using the bomb washing method according to ASTM E 775 - 87. Therefore, in this study, heating value and sulfur analyses of rubber were not conducted.

In ultimate analysis (dry basis) of each type of solid waste, % C, % N and % S were analyzed in laboratory and % H and % O were calculated from the H: O ratio obtained from Tchobanoglous et al (1993). Plastic had the highest carbon, 74.73 %, followed by textile, wood and food waste, 43.75, 41.20 and 41.15 % (dry basis), respectively. Paper had the lowest carbon, 36.61 % (dry basis). Wood had the highest oxygen, 48.66 %, whereas plastic had the lowest oxygen, 15.22 % (dry basis). Comparing carbon in each type of municipal solid waste in this study with the research of Chai and Zakaria (2006), carbon in food waste, paper and wood of municipal solid waste from Penang, Malaysia were 37.97, 41.44, and 44.76 % (dry basis), respectively, which were not much different.

Ultimate analysis (dry basis) of combustible MSW from Salaya Subdistrict Municipality showed the highest level of carbon with an average value of 55.63 %, followed by oxygen, hydrogen, nitrogen and sulfur, 29.44, 5.83, 1.08 and 0.17 % (dry basis), respectively, as shown in **Table 4.7**. Comparing with the study of Saenamnuayphol (2004), carbon, hydrogen, oxygen, nitrogen, sulfur and ash in combustible MSW from Bangkok were 44.70, 2.22, 46.32, 1.75, 0.67 and 4.34 % (dry basis), respectively, it was found that carbon content was the highest as this study.

Table 4.7 Ultimate analysis (dry basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Mean ± SD (% db)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food waste	41.15 ± 1.60	6.69 ± 0.87	39.31 ± 5.10	2.24 ± 0.89	0.23 ± 0.13	10.38 ± 6.28
Plastic	74.73 ± 3.27	4.81 ± 0.44	15.22 ± 1.40	0.17 ± 0.07	0.12 ± 0.10	4.96 ± 3.04
Paper	36.61 ± 1.36	5.66 ± 0.99	41.52 ± 7.28	0.21 ± 0.08	0.08 ± 0.04	15.91 ± 8.21
Wood	41.20 ± 0.70	6.84 ± 0.25	48.66 ± 1.78	0.22 ± 0.11	0.10 ± 0.03	2.98 ± 1.59
Textile	43.75 ± 3.17	8.80 ± 0.72	41.61 ± 3.42	0.93 ± 0.76	0.15 ± 0.13	4.82 ± 3.74
Combustible MSW	55.63 ± 4.67	5.83 ± 0.62	29.44 ± 5.14	1.08 ± 0.47	0.17 ± 0.10	7.85 ± 2.95

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile
db = dry basis

From calculation of ultimate analysis (air dry basis) of each type of solid waste, it was found that carbon contained in plastic was the highest, 74.09 %, followed by textile and wood with the average value of 41.70 and 37.83 %, respectively. Carbon in paper was the lowest, 34.36 %. Carbon, hydrogen, oxygen, nitrogen, sulfur and ash in combustible MSW were 52.49, 6.13, 32.78, 1.02, 0.16 and 7.43 %, respectively, as shown in **Table 4.8**. Comparing results of this study with those of Teerawattana (2010), which had carbon, hydrogen, oxygen, nitrogen, sulfur, chlorine and ash in RDF from On-nut Composting Plant, Bangkok of 55.15, 7.89, 9.53, 1.30, 0.12, 0.73 and 25.27 %, respectively, it was found that carbon, hydrogen, nitrogen and sulfur contents were not much different.

Table 4.8 Ultimate analysis (air dry basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Mean ± SD (% ad)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food waste	36.99 ± 1.46	7.14 ± 0.86	44.23 ± 5.38	2.02 ± 0.84	0.21 ± 0.12	9.41 ± 5.85
Plastic	74.09 ± 3.35	4.86 ± 0.44	15.85 ± 1.37	0.17 ± 0.07	0.12 ± 0.10	4.91 ± 3.00
Paper	34.36 ± 1.26	6.00 ± 0.97	44.40 ± 7.14	0.20 ± 0.07	0.08 ± 0.04	14.98 ± 7.84
Wood	37.83 ± 0.65	7.19 ± 0.22	51.95 ± 1.50	0.20 ± 0.10	0.09 ± 0.02	2.73 ± 1.44
Textile	41.70 ± 3.89	8.91 ± 0.67	43.83 ± 3.14	0.89 ± 0.71	0.14 ± 0.12	4.53 ± 3.41
Combustible MSW	52.49 ± 5.07	6.13 ± 0.66	32.78 ± 5.70	1.02 ± 0.45	0.16 ± 0.10	7.43 ± 2.86

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile
ad = air dry basis

From calculation of ultimate analysis of each type of solid waste from air dry basis to as received basis, it was found that carbon contained in plastic was the highest, 44.38 %, followed by wood and textile, 29.14 and 27.70 % (as received basis), respectively. Carbon in food waste was the lowest, 9.83 %. Combustible MSW had carbon, hydrogen, oxygen, nitrogen, sulfur and ash of 20.95, 9.16, 66.41, 0.40, 0.07 and 3.01 %, respectively, as shown in **Table 4.9**. Comparing results of this study to those of Chang et al (1997), which had carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine in RDF from Taiwan of 20.11, 2.92, 12.58, 0.55, 0.80 and 0.18 %, respectively, it was found that carbon and nitrogen contents were not different while hydrogen, oxygen and sulfur contents were different.

Table 4.9 Ultimate analysis (as received basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Mean ± SD (% ar)					
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food waste	9.83 ± 2.09	10.10 ± 0.38	76.88 ± 3.29	0.56 ± 0.33	0.06 ± 0.05	2.57 ± 1.90
Plastic	44.38 ± 10.10	7.38 ± 0.93	45.18 ± 9.07	0.10 ± 0.06	0.08 ± 0.06	2.87 ± 1.66
Paper	22.72 ± 3.88	7.75 ± 0.96	59.36 ± 7.65	0.13 ± 0.06	0.05 ± 0.03	9.99 ± 6.10
Wood	29.14 ± 6.77	8.10 ± 0.79	60.35 ± 7.08	0.16 ± 0.11	0.07 ± 0.02	2.19 ± 1.52
Textile	27.70 ± 3.94	9.72 ± 0.32	58.99 ± 3.35	0.54 ± 0.35	0.09 ± 0.07	2.96 ± 2.29
Combustible MSW	20.95 ± 4.02	9.16 ± 0.48	66.41 ± 4.60	0.40 ± 0.20	0.07 ± 0.04	3.01 ± 1.40

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile
ar = as received basis

From calculation of ultimate analysis (dry and ash free basis) of each type of solid waste, it was found that plastic had the highest carbon of 78.62 %, followed by food waste, 46.05 %. Wood had the lowest carbon of 42.48 %, while it had the highest oxygen of 50.15 %. Plastic had the lowest oxygen of 16.02 %. Combustible MSW from Salaya Subdistrict Municipality had the highest carbon of 60.44 %, followed by oxygen, 31.88 %. Hydrogen, nitrogen and sulfur were 6.32, 1.18 and 0.18 % (dry and ash free basis), respectively, as shown in **Table 4.10**.

Table 4.10 Ultimate analysis (dry and ash free basis) of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Mean ± SD (% daf)				
	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
Food waste	46.05 ± 2.54	7.44 ± 0.49	43.71 ± 2.91	2.54 ± 1.11	0.27 ± 0.16
Plastic	78.62 ± 1.95	5.06 ± 0.47	16.02 ± 1.48	0.18 ± 0.07	0.12 ± 0.11
Paper	43.90 ± 4.44	6.69 ± 0.53	49.07 ± 3.88	0.25 ± 0.08	0.10 ± 0.05
Wood	42.48 ± 1.17	7.05 ± 0.16	50.15 ± 1.13	0.23 ± 0.12	0.10 ± 0.03
Textile	45.95 ± 2.93	9.24 ± 0.58	43.66 ± 2.73	0.99 ± 0.82	0.16 ± 0.14
Combustible MSW	60.44 ± 5.62	6.32 ± 0.54	31.88 ± 4.95	1.18 ± 0.54	0.18 ± 0.11

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile
daf = dry and ash free basis

4.2 Heating values of solid waste from analysis

Heating values (dry basis) analysis of each type of solid waste that had been ground and dried at 107 ^{o}C were determined. Heating value of combustible MSW from Salaya Subdistrict Municipality was calculated from its physical composition. Food waste, plastic, paper, wood and textile had higher heating values (HHV) in the range of 3,693 – 4,856, 8,875 – 10,712, 3,279 – 3,859, 4,458 – 4,634 and 4,043 – 5,043 cal/g (dry basis), respectively, and combustible MSW had HHV of 5,792 – 7,660 cal/g (dry basis), as shown in **Table 4.11**.

The average value of HHV of wood in this study was 4,541 cal/g (dry basis) while Sørum et al (2001) found that HHV of spruce wood was 4,611 cal/g (dry basis).

HHV of food waste and paper in this study were 4,326 and 3,653 cal/g (dry basis), respectively. HHV of food waste and paper in the study of Menikpura and Basnayake (2009) were 4,396 and 3,584 cal/g (dry basis), respectively, which were close to those of this study.

HHV (air dry basis) of food waste, plastic, paper, wood and textile were 3,397 – 4,322, 8,816 – 10,665, 3,101 – 3,618, 4,083 – 4,289 and 3,838 – 4,936 cal/g, respectively. Combustible MSW had HHV of 5,373 – 7,269 cal/g with an average of 6,316 cal/g (air dry basis) as shown in **Table 4.11**. Heating values of RDF from On-nut Composting Plant, Bangkok in the study of Teerawattana et al (2011) were

5,811 – 7,958 cal/g with an average of 6,888 cal/g (air dry basis), which did not show a big difference.

Table 4.11 Heating values of each type of solid waste and combustible MSW from Salaya Subdistrict Municipality

Components	Range of HHV cal/g (db)	Mean ± SD of HHV cal/g (db)	Range of HHV cal/g (ad)	Mean ± SD of HHV cal/g (ad)
Food waste	3,693 - 4856	4,326 ± 351	3,397 - 4,322	3,887 ± 284
Plastic	8,875 - 10,712	9,894 ± 633	8,816 - 10,665	9,809 ± 632
Paper	3,279 - 3,859	3,653 ± 220	3,101 - 3,618	3,427 ± 188
Wood	4,458 - 4,634	4,541 ± 56	4,083 - 4,289	4,170 ± 65
Textile	4,043 - 5,043	4,563 ± 423	3,838 - 4,936	4,352 ± 490
Combustible MSW	5,792 - 7,660	6,694 ± 659	5,373 - 7,269	6,316 ± 689

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

db = dry basis

ad = air dry basis

4.3 Heating values predicted by equations

4.3.1 Heating values predicted by physical composition based model

The average HHV of combustible MSW from Salaya Subdistrict Municipality calculated by using Equation 2.7, HHV_{ad} (cal/g) = 5,383.541 + 0.457 P_{ad}^{2}, of Teerawattana et al (2011) was 6,195 cal/g (air dry basis) with the AAE of 3.33 % as shown in **Table 4.12**.

Table 4.12 Heating values of combustible MSW (air dry basis) predicted by physical composition based model

No. of Combustible municipal solid waste sample	Plastic (% ad)	HHV calculated from Eq. (2.7) cal/g (ad)	% AE of Eq. (2.7)	HHV from measurement, cal/g (ad)
1	20.62	5,578	3.81	5,373
2	29.81	5,790	0.95	5,845
3	34.91	5,940	2.55	6,096
4	54.24	6,728	7.44	7,269
5	50.69	6,558	1.88	6,437
6	53.70	6,701	6.23	7,147
7	38.84	6,073	0.45	6,046
Average	40.40	6,195	3.33	6,316
SD	12.98	465		689

Remark: ad = air dry basis

Eq. (2.7): HHV_{ad} (cal/g) = 5,383.541 + 0.457 $P_{ad}{}^{2}$

from Teerawattana et al (2011)

Absolute error, or AE (%) = $\left|\frac{\text{calculated value} - \text{measured value}}{\text{measured value}}\right| \times 100$

Average absolute error, or AAE (%) = $\frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value} - \text{measured value}}{\text{measured value}}\right| \times 100$

4.3.2 Heating values predicted by proximate analysis based model

HHV of each type of solid waste and combustible MSW were calculated by using in Equation 2.9, HHV_{db} (MJ/kg) = 19.914 - ($0.2324A_{db}$), of Sheng and Azevedo (2005). It was found that the predicted heating values of most types of solid waste were similar to the values measured in this study. Wood, in particular, had AAE of 2.02 %, and food waste, paper and textile had AAE of 4.73, 6.85 and 6.90 %, respectively. Plastic had the highest AAE, 54.61 %, compared to other types of waste. This may be because this equation was applied to biomass fuels, which did not include plastic. AAE of combustible MSW was high, 34.90 %. This may be because there was a high percentage of plastic in combustible MSW, therefore calculated value was quite different from measured value as shown in **Table 4.13**.

Table 4.13 Heating values of each type of solid waste and combustible MSW (dry basis) predicted by proximate analysis based model

Components	Mean ± SD of ash (% db)	Mean ± SD of HHV calculated from Eq. (2.9) cal/g (db)	% AAE of Eq. (2.9)	Mean ± SD of HHV from measurement, cal/g (db)
Food waste	10.38 ± 6.28	4,181 ± 349	4.73	4,326 ± 351
Plastic	4.96 ± 3.04	4,482 ± 169	54.61	9,894 ± 633
Paper	15.91 ± 8.21	3,874 ± 456	6.85	3,653 ± 220
Wood	2.98 ± 1.59	4,592 ± 88	2.02	4,541 ± 56
Textile	4.82 ± 3.74	4,490 ± 208	6.90	4,563 ± 423
Combustible MSW	7.85 ± 2.95	4,321 ± 164	34.90	6,694 ± 659

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

db = dry basis

Eq. (2.9): HHV_{db} (MJ/kg) = 19.914 - ($0.2324A_{db}$) from Sheng and Azevedo (2005)

Average absolute error, $\text{AAE (\%)} = \frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value}-\text{measured value}}{\text{measured value}}\right| \times 100$

4.3.3 Heating values predicted by ultimate analysis based models

The ultimate analysis based models selected were equations applied to solid waste and similar materials. Due to limited clarity of equations on basis in ultimate analysis and types of heating value (HHV or LHV), only some equations were selected, which were divided into two groups based on moisture in the waste as follows.

Group 1: dry basis. Equation 2.21, HHV_{db} (MJ/kg) = $0.3259C_{db}$ + 3.4597, and Equation 2.22, HHV_{db} (MJ/kg) = -1.3675 + $0.3137C_{db}$ + $0.7009H_{db}$ + $0.0318O_{db}^{*}$, of Sheng and Azevedo (2005) were employed. These equations were applied with many kinds of biomass fuels such as olive seeds, hay, oak sawdust, eucalyptus sawdust, almond shell, hazelnut shell, corncob, etc.

Group 2: air dry basis. Equation 2.23, HHV_{ad} (cal/g) = 135.505 C_{ad}, of Teerawattana et al (2011) was employed. This equation was applied with RDF from On-nut Composting Plant, Bangkok, Thailand.

The heating values of each type of solid waste and combustible MSW predicted from the equations mentioned above are as follows.

1) Heating values predicted by group 1 Equations

Heating values of paper predicted by Equation 2.22 of Sheng and Azevedo (2005) were the closest to the measured values with AAE of 1.48 %. It was also found that predicted heating values of food waste, wood and textile were similar to those of the measured values with AAE of 3.19, 5.78 and 5.13 %, respectively. The heating values of plastic predicted by Equations 2.21 and 2.22 of Sheng and Azevedo (2005), were different from the measured values in this study with AAE of 32.70 and 37.25 %, respectively. The measured heating values of combustible MSW in this study were different from those predicted by Equations 2.21 and 2.22 of Sheng and Azevedo (2005) with AAE of 22.76 and 24.21 %, respectively, as shown in **Table 4.14**. This might be because these equations were applied with biomass fuels only, not plastic.

Table 4.14 Heating values of each type of solid waste and combustible MSW (dry basis) predicted by ultimate analysis based models

Components	Mean ± SD of carbon (% db)	Mean ± SD of hydrogen (% db)	Mean ± SD of oxygen* (% db)	Mean ± SD of HHV calculated from Eq. (2.21), cal/g (db)	% AAE of Eq. (2.21)	Mean ± SD of HHV calculated from Eq. (2.22), cal/g (db)	% AAE of Eq. (2.22)	Mean ± SD of HHV from measurement, cal/g (db)
Food waste	41.15 ± 1.60	6.69 ± 0.87	41.78 ± 4.58	4,030 ± 125	7.50	4,195 ± 254	3.19	4,326 ± 351
Plastic	74.73 ± 3.27	4.81 ± 0.44	15.51 ± 1.42	6,645 ± 255	32.70	6,196 ± 224	37.25	9,894 ± 633
Paper	36.61 ± 1.36	5.66 ± 0.99	41.81 ± 7.34	3,677 ± 106	3.73	3,683 ± 228	1.48	3,653 ± 220
Wood	41.20 ± 0.70	6.84 ± 0.25	48.98 ± 1.67	4,034 ± 55	11.15	4,278 ± 47	5.78	4,541 ± 56
Textile	43.75 ± 3.17	8.80 ± 0.72	42.62 ± 2.98	4,233 ± 247	6.98	4,750 ± 225	5.13	4,563 ± 423
Combustible MSW	55.63 ± 4.67	5.83 ± 0.62	30.69 ± 5.24	5,158 ± 364	22.76	5,051 ± 251	24.21	6,694 ± 659

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

db = dry basis

Eq. (2.21): HHV_{db} (MJ/kg) = $0.3259C_{db} + 3.4597$ from Sheng and Azevedo (2005)

Eq. (2.22): HHV_{db} (MJ/kg) = $(-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$ from Sheng and Azevedo (2005)

When $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Average absolute error, $\text{AAE (\%)} = \frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value} - \text{measured value}}{\text{measured value}}\right| \times 100$

2) Heating values predicted by group 2 Equation

Heating values of plastic predicted by Equation 2.23 of Teerawattana et al (2011) were the most accurate, 4.37 % AAE, comparing with other types of solid waste. It was also found that predicted heating values of paper were not accurate, 36.11 % AAE. Heating values of combustible MSW were not accurate with AAE of 12.78 % as shown in **Table 4.15**.

Table 4.15 Heating values of each type of solid waste and combustible MSW (air dry basis) predicted by ultimate analysis based model

Components	Mean ± SD of Carbon (% ad)	Mean ± SD of HHV calculated from Eq. (2.23), cal/g (ad)	% AAE of Eq.(2.23)	Mean ± SD of HHV from measurement, cal/g (ad)
Food waste	36.99 ± 1.46	5,013 ± 198	29.34	3,887 ± 284
Plastic	74.09 ± 3.35	10,040 ± 454	4.37	9,809 ± 632
Paper	34.36 ± 1.26	4,655 ± 171	36.11	3,427 ± 188
Wood	37.83 ± 0.65	5,126 ± 88	22.94	4,170 ± 65
Textile	41.70 ± 3.89	5,651 ± 527	30.10	4,352 ± 490
Combustible MSW	52.49 ± 5.07	7,113 ± 688	12.78	6,316 ± 689

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

ad = air dry basis

Eq. (2.23): HHV_{ad} (cal/g) = 135.505C_{ad} from Teerawattana et al (2011)

Average absolute error, $\text{AAE (\%)} = \frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value}-\text{measured value}}{\text{measured value}}\right| \times 100$

4.4 Determination of heating values by using Hess's law

4.4.1 Method of calculating heating values by using Hess's law

Ultimate analysis data were determined by changing basis from dry basis to dry and ash free basis, then divided by atomic weight and adjusted carbon atom into full number to get chemical formulae of each type of solid waste and combustible MSW. Chemical formulae of food waste, plastic, paper, wood, textile and combustible MSW were $C_6H_{11.63}O_{4.27}N_{0.28}S_{0.01}$, $C_6H_{4.63}O_{0.92}N_{0.01}$, $C_6H_{10.98}O_{5.03}N_{0.03}$,

$C_6H_{11.94}O_{5.31}N_{0.03}S_{0.01}$, $C_6H_{14.47}O_{4.28}N_{0.11}S_{0.01}$ and $C_6H_{7.53}O_{2.37}N_{0.10}S_{0.01}$, respectively. When molecular weight of each type of solid waste and combustible MSW were calculated, it was found that molecular weight of plastic was the lowest, 91.58, comparing with molecular weight of other types of solid waste as shown in **Table 4.16**.

Table 4.16 Molecular formulae and molecular weights of each type of solid waste and combustible MSW

Components	Chemical formula	Molecular weight
Food waste	$C_6H_{11.63}O_{4.27}N_{0.28}S_{0.01}$	156.35
Plastic	$C_6H_{4.63}O_{0.92}N_{0.01}$	91.58
Paper	$C_6H_{10.98}O_{5.03}N_{0.03}$	164.02
Wood	$C_6H_{11.94}O_{5.31}N_{0.03}S_{0.01}$	169.49
Textile	$C_6H_{14.47}O_{4.28}N_{0.11}S_{0.01}$	156.70
Combustible MSW	$C_6H_{7.53}O_{2.37}N_{0.10}S_{0.01}$	119.13

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

Chemical formulae of each type of solid waste and combustible MSW were substituted in Equation 2.3.

$$C_uH_vO_wN_xS_y + \left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right)(O_2 + 3.75N_2)$$

$$\rightarrow uCO_2 + \frac{v}{2}H_2O + ySO_2 + [3.75\left(u + \left(\frac{v}{4}\right) - \left(\frac{w}{2}\right) + y\right) + \frac{x}{2}]N_2 \quad \text{.......(2.3)}$$

From complete combustion equation, heat of formation of products were calculated by Equation 3.4 or 3.5.

Heat of formation of products = Σ {(mole of product) × Δ H_f° (product)}..........(3.4)

Or

Heat of formation of products = moles of CO_2 × Δ H_f° $(CO_2)_{(g)}$ + moles of H_2O × Δ H_f° $(H_2O)_{(l)}$ + moles of SO_2 × Δ H_f° $(SO_2)_{(g)}$...(3.5)

When Δ H_f^o of $CO_{2\,(g)}$, $H_2O_{(l)}$ and $SO_{2\,(g)}$ are as follows

$C_{(s)} + O_{2\,(g)} \rightarrow CO_{2\,(g)}$ ΔH_f^o of $CO_{2\,(g)}$ = -94.01 kcal/mole…………….…(3.6)

$H_{(g)} + ½\, O_{2\,(g)} \rightarrow H_2O_{(l)}$ ΔH_f^o of $H_2O_{(l)}$ = -68.28 kcal/mole………………(3.7)

$S_{(s)} + O_{2\,(g)} \rightarrow SO_{2\,(g)}$ ΔH_f^o of $SO_{2\,(g)}$ = -70.91 kcal/mole………………(3.8)

Heat of reaction was the measured heating value (dry basis) which was changed from cal/g to kcal/mole. Heat of formation of reactants was calculated from heat of formation of products minus heat of reaction.

Average values of heat of formation of products calculated from complete combustion of food waste, paper, wood and textile were similar with -964, -945, -973 and -1,062 kcal/mole, respectively. Heat of formation of products of plastic was -723 kcal/mole. Combustible MSW had heat of formation of products of -825 kcal/mole. Average values of heat of formation of reactants of paper and textile were similar, –339 and -348 kcal/mole, respectively. Average values of heat of formation of reactants of food waste, plastic, wood and combustible MSW were –285, 183, -203 and -27 kcal/mole, respectively, as shown in **Table 4.17**.

Table 4.17 Calculated heat of formation of products and heat of formation of reactants and measured heat of reaction in combustion of each type of solid waste and combustible MSW

Components	Mean ± SD			
	Heat of formation of products (from calculation)	Heat of reaction (from measurement)		Heat of formation of reactants (from calculation)
	(kcal/mole)	(kcal/mole)	(cal/g)	(kcal/mole)
Food waste	-964 ± 49	-679 ± 75	-4,326 ± 351	-285 ± 50
Plastic	-723 ± 19	-906 ± 59	-9,894 ± 633	183 ± 57
Paper	-945 ± 74	-607 ± 91	-3,653 ± 220	-339 ± 30
Wood	-973 ± 20	-770 ± 20	-4,541 ± 56	-203 ± 9
Textile	-1,062 ± 66	-715 ± 36	-4,563 ± 423	-348 ± 81
Combustible MSW	-825 ± 47	-798 ± 39	-6,694 ± 659	-27 ± 54

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

4.4.2 Construction of equation for heating values prediction

In constructing equation for heating values determination, the independent variable was heat of formation of products because it can be calculated by ultimate analysis data. The dependent variable was heat of reaction. The unit of each variable was kcal/mole. The relationship between heat of reaction and heat of formation of products of five types of solid waste (food waste, plastic, paper, wood and textile) was in linear, as shown in **Figure 4.1** and Equation 4.1.

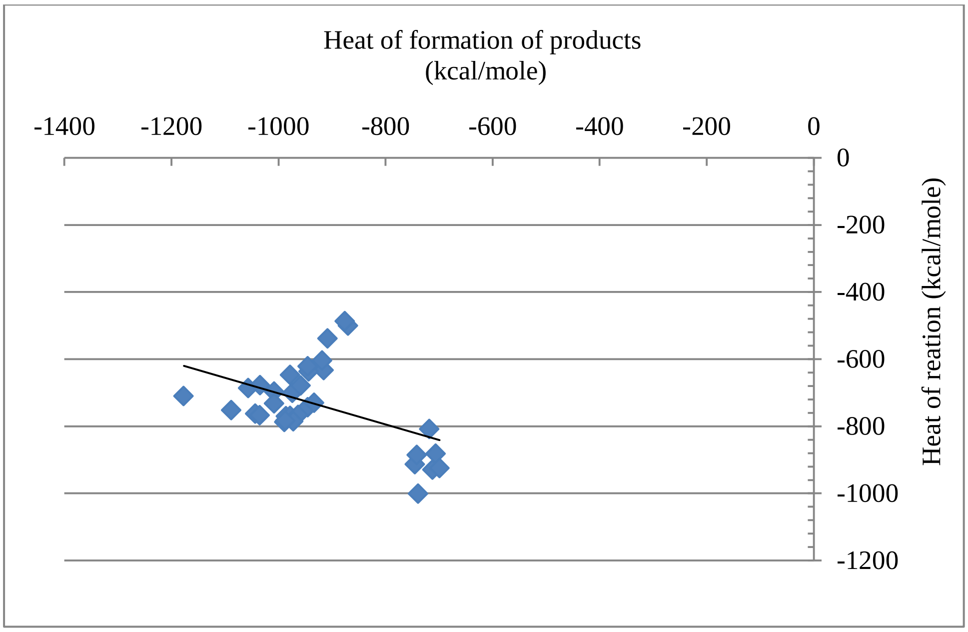

Figure 4.1 Relationship between heat of reaction (kcal/mole) and heat of formation of products (kcal/mole) of five types of solid waste

$$Y= -0.4630X – 1,165.2753 \quad \text{.................................. (4.1)}$$

When Y = heat of reaction (kcal/mole)

X = heat of formation of products (kcal/mole)

From Equation 4.1, it was found that heat of reaction was correlated to heat of formation of products at a significance level of 0.05. Beta of constant and heat of formation of products were -1,165.2753 and -0.4630, respectively. Relationship between heat of reaction and heat of formation of products was in the opposite direction. This means that heat of formation of products was decreased leading to increased heat of reaction. P value of constant and heat of formation of products were <0.001 and 0.006, respectively as shown in **Table 4.18**, which was less than 0.05 meaning that relationship of the two variable was significant.

Table 4.18 Coefficients of Equation 4.1

	Model	Unstandardized coefficients	Sig.
		B	
4.1	Constant	-1,165.2753	< 0.001
	Heat of formation of products	-0.4630	0.006

It was also found that Equation 4.1 had standard error of estimate of 108.0381 and coefficient of determination (R square) of 0.2209, as shown in **Table 4.19**. This means that heat of formation of products can explain 22.09 % of heat of reaction and 77.91 % is the result of other factors not taken into account in this equation. This might be because the sample size used in this study was small, only 7 samples.

Table 4.19 R square and standard error of estimate of Equation 4.1

Model	R square	Standard error of estimate
4.1	0.2209	108.0381

From calculation by Equation 4.1, heat of reaction (kcal/mole) of combustible MSW from Salaya Subdistrict Municipality was close to heat of reaction measured in this study with AAE of 5.60 %. While heat of reaction (kcal/mole) of plastic, wood and textile showed AAE of 8.90, 7.22 and 6.07 %, respectively. Heat of reaction (kcal/mole) of food waste and paper were different from the measured values in this study with AAE of 10.95 and 26.37 %, respectively, as shown in **Table 4.20**.

Table 4.20 Heat of reaction (kcal/mole) predicted by Hess's law based model

Components	Mean ± SD of Heat of reaction calculated from Eq. (4.1) (kcal/mole)	% AAE of Eq. (4.1)	Mean ± SD of Heat of reaction from measurement, (kcal/mole)
Food waste	-719 ± 22	10.95	-679 ± 75
Plastic	-831 ± 9	8.90	-906 ± 59
Paper	-728 ± 34	26.37	-607 ± 91
Wood	-715 ± 9	7.22	-770 ± 20
Textile	-674 ± 31	6.07	-715 ± 36
Combustible MSW	-783 ± 22	5.60	-798 ± 39

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

Eq. (4.1): Y= -0.4630X – 1,165.2753

When Y = heat of reaction (kcal/mole)

X = heat of formation of products (kcal/mole)

Average absolute error, $\text{AAE (\%)} = \frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value}-\text{measured value}}{\text{measured value}}\right| \times 100$

4.5 Comparison of predicted heating values

Heating values of each type of municipal solid waste and combustible MSW predicted by physical composition, proximate analysis and ultimate analysis based models and Hess's law based model were compared with those measured by bomb calorimeter. The results can be categorized by types of equation as follows.

4.5.1 Physical composition based model

Equation 2.7 of Teerawattana et al (2011) gave the close prediction of heating value of combustible MSW from Salaya Subdistrict Municipality to the measured value with AAE of 3.33%, as shown in **Table 4.21**.

4.5.2 Proximate analysis based model

Equation 2.9 of Sheng and Azevedo (2005) gave the close prediction of heating values of food waste, paper, wood and textile to the measured value with AAE of 4.73, 6.85, 2.02 and 6.90 %, respectively.

4.5.3 Ultimate analysis based models

Equation 2.21 of Sheng and Azevedo (2005) gave the close prediction of heating values of food waste, paper and textile to the measured values with AAE of 7.50, 3.73 and 6.98 %, respectively.

Equation 2.22 of Sheng and Azevedo (2005) gave the close prediction of heating values of food waste, paper, wood and textile to the measured values with AAE of 3.19, 1.48, 5.78 and 5.13 %, respectively.

Equation 2.23 of Teerawattana et al (2011) gave the close prediction of heating value of plastic to the measured value with AAE of 4.37 %.

4.5.4 Hess's law based model

Equation 4.1 gave the close prediction of heating values of plastic, wood, textile and combustible MSW to the measured values with AAE of 8.90, 7.22, 6.07 and 5.60 %, respectively.

According to the predicted heating values of each type of solid waste and combustible MSW from different equations, it was found that physical composition based model (Equation 2.7) and ultimate analysis based model (Equation 2.23) of Teerawattana et al (2011) could predict more precisely for combustible MSW and plastic, respectively. The proximate analysis based model (Equation 2.9) and ultimate analysis based models (Equations 2.21 and 2.22) of Sheng and Azevedo (2005), applied to biomass fuel, could precisely predict heating values of some types of municipal solid waste namely food waste, paper, wood and textile.

In constructed model based on Hess's law, Equation 4.1, heat of reaction was correlated to heat of formation of products at a significance level of 0.05, but with low coefficient of determination (R^2 = 0.2209). This might be because the sample size used in this study was small, only 7 samples. However, when Equation 4.1 was used for predicting heating values of solid waste, it was found that the predicted heating values were not different from those predicted by physical composition, proximate analysis and ultimate analysis based models, as shown in **Table 4.21**. Therefore, further studies on the Hess's law based model for determining heating value should be conducted by using large sample size.

Table 4.21 Comparison of % AAE of prediction by Equations 2.7, 2.9, 2.21, 2.22, 2.23 and 4.1

Components	Physical composition based model	Proximate analysis base model	Ultimate analysis based model			Hess's law based model
	% AAE of Eq. (2.7)	% AAE of Eq. (2.9)	% AAE of Eq. (2.21)	% AAE of Eq. (2.22)	% AAE of Eq. (2.23)	% AAE of Eq. (4.1)
Food waste	-	4.73	7.50	3.19	29.34	10.95
Plastic	-	54.61	32.70	37.25	4.37	8.90
Paper	-	6.85	3.73	1.48	36.11	26.37
Wood	-	2.02	11.15	5.78	22.94	7.22
Textile	-	6.90	6.98	5.13	30.10	6.07
Combustible MSW	3.33	34.90	22.76	24.21	12.78	5.60

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

Eq. (2.7): HHV_{ad} (cal/g) = 5,383.541 + 0.457 $P_{ad}{}^{2}$ from Teerawattana et al (2011)

Eq. (2.9): HHV_{db} (MJ/kg) = 19.914 - (0.2324A_{db}) from Sheng and Azevedo (2005)

Eq. (2.21): HHV_{db} (MJ/kg) = 0.3259C_{db} + 3.4597 from Sheng and Azevedo (2005)

Eq. (2.22): HHV_{db} (MJ/kg) = (-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*} from Sheng and Azevedo (2005)

When $O_{db}^{*} = 100 – C_{db} – H_{db} – A_{db}$

Eq. (2.23): HHV_{ad} (cal/g) = 135.505C_{ad} from Teerawattana et al (2011)

Eq. (4.1): Y = -0.4630X – 1,165.2753

When Y = heat of reaction (kcal/mole)

X = heat of formation of products (kcal/mole)

Average absolute error, AAE (%) $= \frac{1}{n}\sum_{i=n}^{n}\left|\frac{\text{calculated value}-\text{measured value}}{\text{measured value}}\right| \times 100$

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

There are two topics in this chapter: 1) conclusions and 2) recommendations.

5.1 Conclusions

5.1.1 Physical composition of municipal solid waste

Physical composition of municipal solid waste in Salaya Subdistrict Municipality (as received basis) including food waste, plastic, paper, wood, textile, rubber, foam, glass, metal, rubble, hazardous waste and miscellaneous were 58.55, 24.95, 4.56, 1.66, 1.13, 1.14, 1.75, 3.34, 0.58, 0.75, 0.09 and 1.51 %, respectively. Physical composition of combustible MSW (air dry basis) namely food waste, plastic, paper, wood, textile and rubber were 43.01, 40.40, 8.19, 3.50, 1.97 and 2.92 %, respectively. Physical composition of combustible MSW (dry basis) namely food waste, plastic, paper, wood, textile and rubber were 41.11, 42.26, 8.14, 3.41, 1.98 and 3.10 %, respectively.

5.1.2 Proximate analysis of solid waste

Proximate analysis (as received basis) included total moisture, combustible matter and ash. Average values of total moisture in food waste, plastic, paper, wood, textile and rubber were 76.08, 40.84, 37.83, 29.34, 36.28 and 6.52 %, respectively. Average values of combustible matter in food waste, plastic, paper, wood, textile and rubber were 21.35, 56.29, 52.19, 68.47, 60.76 and 67.36 %, respectively. Average values of ash in food waste, plastic, paper, wood, textile and rubber were 2.57, 2.87, 9.98, 2.19, 2.96 and 26.13 %, respectively. Combustible MSW (food waste, plastic, paper, wood, textile and rubber) had total moisture, combustible matter and ash at the averages of 61.84, 34.90 and 3.25 %, respectively.

Proximate analysis (air dry basis) included residual moisture, combustible matter and ash. Average values of residual moisture in food waste, plastic, paper, wood, textile and rubber were 10.09, 0.86, 6.16, 8.18, 4.75 and 0.46 %, respectively. Average values of combustible matter in food waste, plastic, paper, wood, textile and rubber were 80.51, 94.23, 78.86, 89.09, 90.71 and 71.58 %, respectively. Average values of ash in food waste, plastic, paper, wood, textile and rubber were 9.40, 4.91, 14.97, 2.73, 4.53 and 27.96 %, respectively. Combustible MSW had residual moisture, combustible matter and ash at the averages of 5.55, 86.55 and 7.89 %, respectively.

In proximate analysis (dry basis), it was found that average values of combustible matter in food waste, plastic, paper, wood, textile and rubber were 89.62, 95.04, 84.09, 97.02, 95.18 and 71.90 %, respectively. Average values of ash in food waste, plastic, paper, wood, textile and rubber were 10.38, 4.96, 15.91, 2.98, 4.82 and 28.10 %, respectively. Combustible MSW had combustible matter and ash at the averages of 91.66 and 8.34 %, respectively.

5.1.3 Ultimate analysis of solid waste

Ultimate analysis (dry basis) included carbon, hydrogen, oxygen, nitrogen, sulfur and ash. Carbon in food waste, plastic, paper, wood and textile were 41.15, 74.73, 36.61, 41.20 and 43.75 %, respectively. Hydrogen in food waste, plastic, paper, wood and textile were 6.69, 4.81, 5.66, 6.84 and 8.80 %, respectively. Oxygen in food waste, plastic, paper, wood and textile were 39.31, 15.22, 41.52, 48.66 and 41.61 %, respectively. Nitrogen in food waste, plastic, paper, wood and textile were 2.24, 0.17, 0.21, 0.22 and 0.93 %, respectively. Sulfur in food waste, plastic, paper, wood and textile were 0.23, 0.12, 0.08, 0.10 and 0.15 %, respectively. Ash of food waste, plastic, paper, wood and textile were 10.38, 4.96, 15.91, 2.98 and 4.82 %, respectively. Combustible MSW from Salaya Subdistrict Municipality had carbon, hydrogen, oxygen, nitrogen, sulfur and ash of 55.63, 5.83, 29.44, 1.08, 0.17 and 7.85 %, respectively.

Ultimate analysis (air dry basis) showed that carbon in food waste, plastic, paper, wood and textile had averages of 36.99, 74.09, 34.36, 37.83 and 41.70 %, respectively. Hydrogen in food waste, plastic, paper, wood and textile had averages of 7.14, 4.86, 6.00, 7.19 and 8.91 %, respectively. Oxygen in food waste, plastic, paper, wood and textile had averages of 44.23, 15.85, 44.40, 51.95 and 43.83 %, respectively. Nitrogen in food waste, plastic, paper, wood and textile had averages of 2.02, 0.17, 0.20, 0.20 and 0.89 %, respectively. Sulfur in food waste, plastic, paper, wood and textile had averages of 0.21, 0.12, 0.08, 0.09 and 0.14 %, respectively. Ash in food waste, plastic, paper, wood and textile had averages of 9.41, 4.91, 14.98, 2.73 and 4.53 %, respectively. Combustible MSW had averages of carbon, hydrogen, oxygen, nitrogen, sulfur and ash of 52.49, 6.13, 32.78, 1.02, 0.16 and 7.43 %, respectively.

5.1.4 Heating values of solid waste

Average values of HHV of food waste, plastic, paper, wood and textile were 4,326, 9,894, 3,653, 4,541 and 4,563 cal/g (dry basis), respectively and average HHV of combustible MSW from Salaya Subdistrict Municipality was 6,694 cal/g (dry basis).

HHV (air dry basis) of food waste, plastic, paper, wood and textile were at the averages of 3,887, 9,809, 3,427, 4,170 and 4,352 cal/g, respectively. HHV of combustible MSW from Salaya Subdistrict Municipality was at the average of 6,316 cal/g.

5.1.5 Comparison of predicted heating values

Heating values of each type of municipal solid waste and combustible MSW predicted by physical composition, proximate analysis and ultimate analysis based models and Hess's law based model were compared with those measured by bomb calorimeter. The results can be categorized by types of equation as follows.

1) Physical composition based model

Equation 2.7, HHV_{ad} (cal/g) = 5,383.541 + 0.457 P_{ad}^2, an equation of Teerawattana et al (2011), gave the close prediction of heating value of combustible MSW from Salaya Subdistrict Municipality to the measured value with AAE of 3.33 %.

2) Proximate analysis based model

Equation 2.9, HHV_{db} (MJ/kg) = 19.914 - ($0.2324A_{db}$), an equation of Sheng and Azevedo (2005), gave the close prediction of heating values of food waste, paper, wood and textile to the measured values with AAE of 4.73, 6.85, 2.02 and 6.90 %, respectively.

3) Ultimate analysis based model

Equation 2.21, HHV_{db} (MJ/kg) = $0.3259C_{db} + 3.4597$, an equation of Sheng and Azevedo (2005) gave the close prediction of heating values of food waste, paper and textile to the measured values with AAE of 7.50, 3.73 and 6.98 %, respectively.

Equation 2.22, HHV_{db} (MJ/kg) = $(-1.3675) + 0.3137C_{db} + 0.7009H_{db} + 0.0318O_{db}^{*}$, an equation of Sheng and Azevedo (2005), gave the close prediction of heating values of food waste, paper, wood and textile to the measured values with AAE of 3.19, 1.48, 5.78 and 5.13 %, respectively.

Equation 2.23, HHV_{ad} (cal/g) = $135.505C_{ad}$, an equation of Teerawattana et al (2011), gave the close prediction of heating value of plastic to the measured value with AAE of 4.37 %.

4) Hess's law based model

Comparison of heating values predicted by Hess's law based equation (Equation 4.1) and other equations, it was found that heating values of solid waste namely plastic, wood, textile, and combustible MSW were not different from those predicted by other equations. AAE's were 8.90, 7.22, 6.07 and 5.60 %, respectively. Even though heat of reaction in Equation 4.1 was correlated to heat of formation of products at a significance level of 0.05, the coefficient of determination was low (R^2 = 0.2209). This might be because the sample size used in this study was small, only 7 samples, therefore large sample size should be used for developing better equation in the futher.

5.2 Recommendations

5.2.1 Recommendations on implementation of results of this study

1) Results of physical composition, proximate analysis, ultimate analysis and heating values of different types of solid waste and combustible MSW from the

Salaya Subdistrict Municipality can be used as basic data in planning of solid waste management, especially in using combustible MSW as fuel.

2) It was found that equations developed from heating values of biomass can predict heating values of wood, paper, textile and food waste better than equations developed with plastic as a variable. This is a guideline for selection of an equation to predict heating value of each type of solid waste.

5.2.2 Recommendations for further studies

1) In proximate analysis, if there is no limitations on analyzing instruments, four parameters namely moisture, volatile matter, fixed carbon and ash should be determined. The model developed from 4 parameters may predict heating values more accurate than the model developed from 3 parameters.

2) More samples of solid waste should be collected in all seasons in order to develop better Hess's law based equation.

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APPENDICES

APPENDIX A

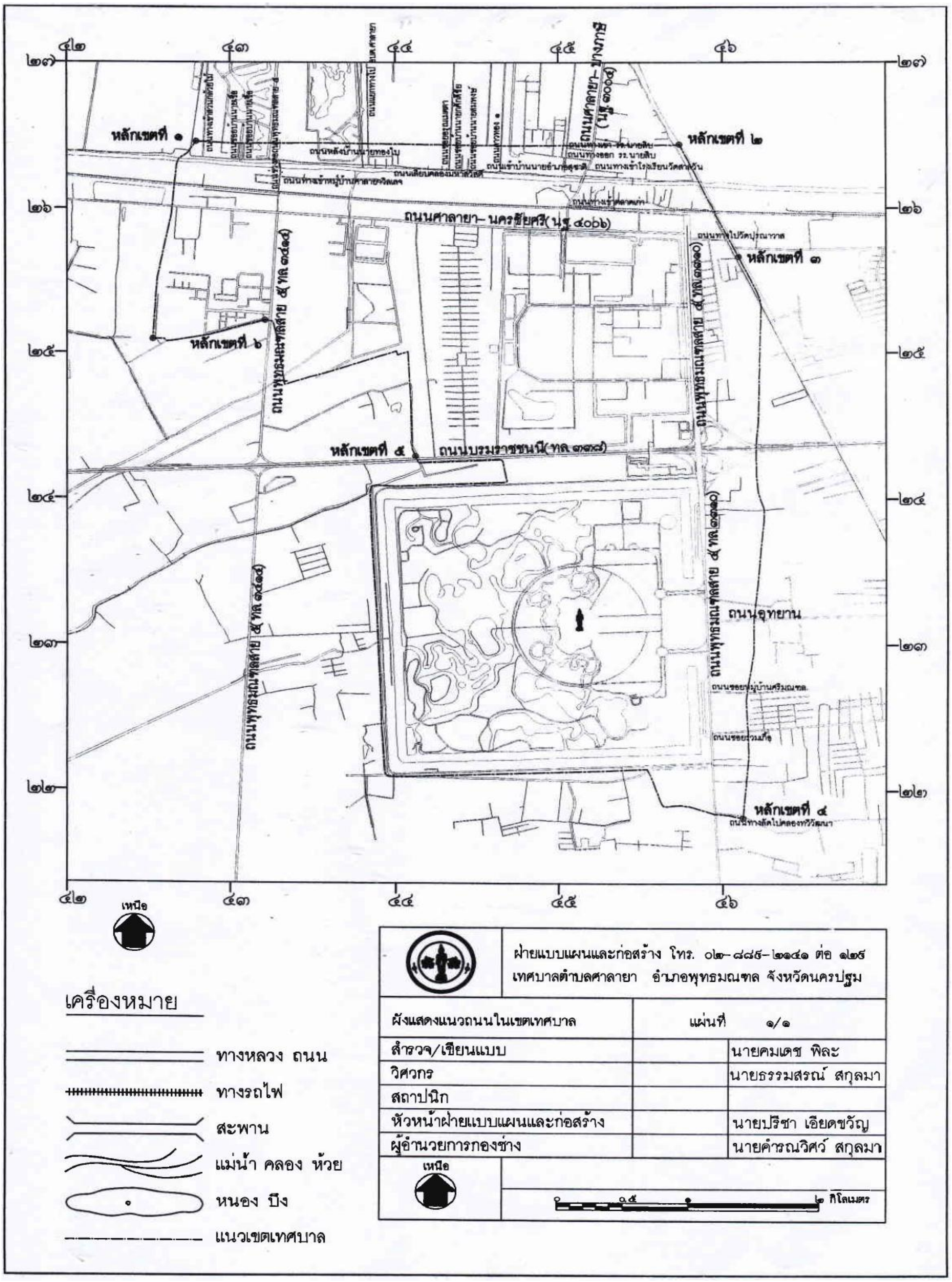

Figure A.1 Map of Salaya Subdistrict Municipality.

APPENDIX B
SAMPLE SIZE CALCULATION

The sample size was calculated by using Equation 3.1 (Vanichbuncha, 2008).

$$n = \frac{Z^2 \times \sigma^2}{e^2} \quad \text{……………………………………………..(3.1)}$$

When n = sample size
Z = values of standard distribution (confidence level = 95%; Z = 1.96)
σ^2 = variance
e = predetermined maximum error

In equation 3.1, sample variance (S^2) was used instead of population variance (σ^2). S^2 can be calculated by the Equation B.1 (Vanichbuncha, 2012). The maximum and minimum heating values from the research of Saenmnuayphol (2004), 2444 and 659 cal/g, respectively, were used in this calculation.

S^2 = (1/36) (maximum value - minimum value)^2…………………..(B.1)
S^2 = (1/36) (2444 - 659)^2
S^2 = 88506 cal/g

Error of heating value is 100 cal/g (Saenamnuayphol, 2004 cited in Srisatit and Boonthawesuk, 1999). The sample size can be calculated as follows.

$$n = \frac{1.96^2 \times 88506}{100^2}$$

$$n = 34$$

Then sample size is 34 samples.

APPENDIX C

RAW DATA OF MSW SAMPLES

Table C.1 Physical composition of MSW in Salaya Subdistrict Municipality, on 1 August 2011 and 8, 11, 17, 23, 26 and 28 February 2012 (as received basis)

Number of sample	% as received basis												Total
	Food waste	Plastic	Paper	Wood	Textile	Rubber	Foam	Glass	Metal	Rubble	Hazardous waste	Miscellaneous	
1	67.65	15.39	3.92	1.96	0.00	0.00	0.49	3.92	0.30	1.96	0.00	4.41	100
2	63.31	18.41	3.39	2.24	0.00	3.91	1.75	1.33	0.80	3.32	0.07	1.47	100
3	60.18	22.36	5.21	2.32	1.60	0.80	2.40	4.81	0.00	0.00	0.00	0.32	100
4	60.02	27.55	4.65	0.54	1.97	0.18	2.23	2.68	0.18	0.00	0.00	0.00	100
5	49.49	31.34	7.10	2.94	1.22	1.12	1.72	3.25	1.01	0.00	0.00	0.81	100
6	54.42	31.79	3.23	0.65	2.15	0.00	2.69	2.48	0.97	0.00	0.54	1.08	100
7	54.79	27.79	4.40	0.98	0.98	1.96	0.98	4.89	0.78	0.00	0.00	2.45	100
average	**58.55**	**24.95**	**4.56**	**1.66**	**1.13**	**1.14**	**1.75**	**3.34**	**0.58**	**0.75**	**0.09**	**1.51**	100
SD	**6.10**	**6.37**	**1.32**	**0.93**	**0.87**	**1.41**	**0.79**	**1.30**	**0.41**	**1.35**	**0.20**	**1.51**	

Remark: Hazardous waste = light bulb

Miscellaneous = sanitary napkin diaper and hypodermic syringe

Table C.2 Physical composition of combustible MSW in Salaya Subdistrict Municipality (as received basis)

Number of sample	% as received basis						Total
	Food waste	Plastic	Paper	Wood	Textile	Rubber	
1	76.07	17.31	4.41	2.21	0.00	0.00	100
2	69.37	20.18	3.71	2.45	0.00	4.29	100
3	65.08	24.18	5.63	2.51	1.73	0.87	100
4	63.24	29.03	4.90	0.57	2.07	0.19	100
5	53.10	33.62	7.62	3.16	1.31	1.20	100
6	59.00	34.46	3.50	0.70	2.34	0.00	100
7	60.28	30.57	4.84	1.08	1.08	2.15	100
average	**63.73**	**27.05**	**4.94**	**1.81**	**1.22**	**1.24**	**100**
SD	**7.45**	**6.64**	**1.39**	**1.02**	**0.93**	**1.55**	

Table C.3 Physical composition of combustible MSW in Salaya Subdistrict Municipality (air dry basis)

Number of sample	% air dry basis						Total
	Food waste	Plastic	Paper	Wood	Textile	Rubber	
1	70.11	20.62	6.41	2.85	0.00	0.00	100
2	48.94	29.81	6.16	4.59	0.00	10.50	100
3	43.24	34.91	11.64	5.09	2.87	2.25	100
4	32.10	54.24	8.91	0.98	3.35	0.42	100
5	25.57	50.69	10.66	7.41	2.80	2.86	100
6	37.03	53.70	4.45	1.34	3.49	0.00	100
7	44.09	38.84	9.09	2.24	1.30	4.44	100
average	**43.01**	**40.40**	**8.19**	**3.50**	**1.97**	**2.92**	**100**
SD	**14.32**	**12.98**	**2.60**	**2.31**	**1.52**	**3.73**	

Table C.4 Physical composition of combustible MSW in Salaya Subdistrict Municipality (dry basis)

Number of sample	% dry basis						Total
	Food waste	Plastic	Paper	Wood	Textile	Rubber	
1	68.52	22.13	6.49	2.85	0.00	0.00	100
2	46.23	31.80	6.19	4.52	0.00	11.26	100
3	41.23	36.75	11.69	4.95	2.99	2.40	100
4	29.77	56.68	8.71	0.94	3.46	0.44	100
5	23.99	52.53	10.57	7.15	2.78	2.98	100
6	35.56	55.46	4.34	1.29	3.35	0.00	100
7	42.48	40.48	9.00	2.14	1.28	4.62	100
average	**41.11**	**42.26**	**8.14**	**3.41**	**1.98**	**3.10**	100
SD	**14.33**	**13.14**	**2.60**	**2.24**	**1.53**	**3.99**	

Table C.5 Physical composition of combustible MSW (except rubber) in Salaya Subdistrict Municipality (as received basis)

Number of sample	% as received basis					Total
	Food waste	Plastic	Paper	Wood	Textile	
1	76.08	17.31	4.41	2.20	0.00	100
2	72.48	21.08	3.88	2.56	0.00	100
3	65.65	24.38	5.68	2.53	1.75	100
4	63.36	29.08	4.91	0.57	2.08	100
5	53.74	34.03	7.71	3.19	1.32	100
6	59.00	34.46	3.50	0.70	2.34	100
7	61.61	31.24	4.95	1.10	1.10	100
average	**64.56**	**27.37**	**5.01**	**1.84**	**1.23**	100
SD	**7.69**	**6.61**	**1.39**	**1.04**	**0.94**	

Table C.6 Physical composition of combustible MSW (except rubber) in Salaya Subdistrict Municipality (air dry basis)

Number of sample	% air dry basis					Total
	Food waste	Plastic	Paper	Wood	Textile	
1	70.11	20.62	6.41	2.85	0.00	100
2	54.68	33.30	6.90	5.12	0.00	100
3	44.23	35.70	11.91	5.22	2.94	100
4	32.23	54.47	8.96	0.97	3.38	100
5	26.32	52.19	10.98	7.63	2.88	100
6	37.03	53.70	4.45	1.34	3.49	100
7	46.14	40.64	9.53	2.34	1.36	100
average	**44.39**	**41.52**	**8.45**	**3.64**	**2.01**	100
SD	**14.71**	**12.71**	**2.66**	**2.43**	**1.54**	

Table C.7 Physical composition of combustible MSW (except rubber) in Salaya Subdistrict Municipality (dry basis)

Number of sample	% dry basis					Total
	Food waste	Plastic	Paper	Wood	Textile	
1	68.52	22.13	6.49	2.85	0.00	100
2	52.08	35.83	6.99	5.09	0.00	100
3	42.23	37.63	11.98	5.07	3.07	100
4	29.90	56.91	8.76	0.95	3.49	100
5	24.72	54.16	10.88	7.38	2.86	100
6	35.56	55.46	4.34	1.29	3.35	100
7	44.53	42.45	9.44	2.24	1.34	100
average	**42.51**	**43.51**	**8.41**	**3.55**	**2.02**	100
SD	**14.70**	**12.83**	**2.66**	**2.36**	**1.55**	

Table C.8 Proximate analysis of food waste (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Food waste 1	68.30	71.26	27.04	1.70	9.33	85.31	5.36	94.09	5.91
Food waste 2	71.73	75.18	24.00	0.82	12.20	84.89	2.90	96.69	3.31
Food waste 3	75.96	78.60	19.52	1.87	11.00	81.21	7.79	91.25	8.75
Food waste 4	79.67	82.10	16.50	1.39	11.97	81.18	6.85	92.21	7.79
Food waste 5	80.69	82.64	15.64	1.72	10.10	81.00	8.90	90.10	9.90
Food waste 6	70.60	72.96	21.07	5.97	8.02	71.68	20.30	77.93	22.07
Food waste 7	67.22	69.84	25.66	4.50	7.98	78.28	13.73	85.07	14.92
average	**73.45**	**76.08**	**21.35**	**2.57**	**10.09**	**80.51**	**9.40**	**89.62**	**10.38**
SD	**5.38**	**5.14**	**4.43**	**1.90**	**1.74**	**4.59**	**5.85**	**6.28**	**6.28**

Table C.9 Proximate analysis of plastic (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Plastic 1	59.02	59.20	40.18	0.62	0.44	98.04	1.52	98.47	1.53
Plastic 2	40.80	41.31	54.46	4.23	0.85	91.99	7.15	92.79	7.21
Plastic 3	47.76	48.67	46.90	4.42	1.74	89.79	8.47	91.38	8.62
Plastic 4	25.16	25.77	72.93	1.31	0.81	97.45	1.74	98.24	1.76
Plastic 5	39.38	39.78	55.39	4.83	0.67	91.36	7.97	91.98	8.02
Plastic 6	27.01	27.79	70.32	1.88	1.07	96.35	2.58	97.39	2.61
Plastic 7	43.07	43.32	53.86	2.82	0.44	94.61	4.96	95.02	4.98
average	**40.31**	**40.84**	**56.29**	**2.87**	**0.86**	**94.23**	**4.91**	**95.04**	**4.96**
SD	**11.70**	**11.57**	**11.77**	**1.66**	**0.45**	**3.23**	**3.00**	**3.04**	**3.04**

Table C.10 Proximate analysis of paper (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Paper 1	50.01	53.02	39.49	7.50	6.02	78.98	15.00	84.04	15.96
Paper 2	33.50	37.91	59.55	2.55	6.63	89.54	3.83	95.90	4.10
Paper 3	25.23	29.90	61.08	9.02	6.25	81.69	12.06	87.13	12.87
Paper 4	27.18	32.43	60.21	7.36	7.20	82.68	10.11	89.10	10.90
Paper 5	43.87	46.66	39.44	13.90	4.97	70.27	24.76	73.94	26.06
Paper 6	40.50	44.44	47.58	7.98	6.63	79.96	13.41	85.63	14.37
Paper 7	15.86	20.43	57.99	21.58	5.43	68.92	25.65	72.88	27.12
average	**33.74**	**37.83**	**52.19**	**9.98**	**6.16**	**78.86**	**14.97**	**84.09**	**15.91**
SD	**11.89**	**11.16**	**9.80**	**6.10**	**0.76**	**7.19**	**7.84**	**8.21**	**8.21**

Table C.11 Proximate analysis of wood (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Wood 1	55.48	58.71	40.36	0.93	7.25	90.65	2.10	97.74	2.26
Wood 2	24.94	31.23	67.45	1.32	8.38	89.87	1.76	98.08	1.92
Wood 3	26.69	33.48	64.38	2.15	9.26	87.81	2.93	96.77	3.23
Wood 4	30.89	36.70	61.96	1.34	8.40	89.65	1.94	97.88	2.12
Wood 5	5.87	12.88	85.41	1.71	7.44	90.74	1.82	98.04	1.96
Wood 6	10.56	17.38	80.16	2.46	7.63	89.62	2.75	97.02	2.98
Wood 7	6.73	15.01	79.54	5.44	8.88	85.29	5.83	93.60	6.40
average	**23.02**	**29.34**	**68.47**	**2.19**	**8.18**	**89.09**	**2.73**	**97.02**	**2.98**
SD	**17.55**	**16.11**	**15.26**	**1.52**	**0.76**	**1.93**	**1.44**	**1.59**	**1.59**

Table C.12 Proximate analysis of textile (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Textile 1	40.14	41.87	56.58	1.55	2.89	94.51	2.60	97.33	2.67
Textile 2	35.20	36.57	62.22	1.21	2.12	96.02	1.86	98.10	1.90
Textile 3	13.94	18.30	79.89	1.81	5.07	92.82	2.10	97.78	2.22
Textile 4	30.08	35.60	57.65	6.74	7.90	82.46	9.64	89.53	10.47
Textile 5	45.94	49.07	47.44	3.49	5.79	87.75	6.45	93.15	6.85
average	**33.06**	**36.28**	**60.76**	**2.96**	**4.75**	**90.71**	**4.53**	**95.18**	**4.82**
SD	**12.20**	**11.39**	**11.97**	**2.29**	**2.32**	**5.57**	**3.41**	**3.74**	**3.74**

Table C.13 Proximate analysis of rubber (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
Rubber 1	1.83	2.21	85.16	12.63	0.38	86.75	12.87	87.08	12.92
Rubber 2	6.19	6.60	55.72	37.68	0.43	59.40	40.16	59.66	40.34
Rubber 3	10.60	11.33	66.07	22.60	0.82	73.91	25.28	74.51	25.49
Rubber 4	4.16	4.28	70.23	25.50	0.12	73.27	26.60	73.36	26.64
Rubber 5	7.67	8.16	59.61	32.23	0.53	64.56	34.91	64.90	35.10
average	**6.09**	**6.52**	**67.36**	**26.13**	**0.46**	**71.58**	**27.96**	**71.90**	**28.10**
SD	**3.34**	**3.52**	**11.43**	**9.56**	**0.25**	**10.44**	**10.41**	**10.47**	**10.47**

Table C.14 Proximate analysis of combustible MSW (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
1	65.60	68.09	30.16	1.75	7.23	87.68	5.09	94.51	5.49
2	59.93	62.76	35.15	2.09	7.06	87.72	5.22	94.38	5.62
3	63.82	66.23	30.56	3.20	6.66	84.49	8.86	90.51	9.49
4	59.95	61.98	36.32	1.70	5.08	90.69	4.23	95.54	4.46
5	59.85	61.51	34.51	3.98	4.14	85.95	9.91	89.66	10.34
6	53.16	55.13	40.24	4.62	4.22	85.91	9.87	89.69	10.31
7	55.19	57.20	37.39	5.41	4.48	83.44	12.08	87.35	12.64
average	**59.64**	**61.84**	**34.90**	**3.25**	**5.55**	**86.55**	**7.89**	**91.66**	**8.34**
SD	**4.38**	**4.58**	**3.61**	**1.48**	**1.38**	**2.40**	**3.02**	**3.12**	**3.12**

Remark: Combustible MSW= mixture of food waste, plastic, paper, wood, textile and rubber

Table C.15 Proximate analysis of combustible MSW (except rubber) (as received basis, air dry basis and dry basis)

Number of sample	Air dry moisture (%)	(%) as received basis			(%) air dry basis			(%) dry basis	
		Total moisture	Combustible matter	Ash	Residual moisture	Combustible matter	Ash	Combustible matter	Ash
1	65.60	68.09	30.16	1.75	7.23	87.68	5.09	94.51	5.49
2	62.53	65.47	32.91	1.62	7.84	87.83	4.32	95.31	4.69
3	64.32	66.75	30.34	2.90	6.80	85.07	8.14	91.27	8.73
4	60.04	62.07	36.27	1.66	5.10	90.76	4.14	95.63	4.37
5	60.52	62.20	34.08	3.72	4.26	86.32	9.42	90.17	9.83
6	53.16	55.13	40.24	4.62	4.22	85.91	9.87	89.69	10.31
7	56.23	58.28	36.90	4.82	4.66	84.32	11.02	88.44	11.55
average	**60.34**	**62.57**	**34.41**	**3.01**	**5.73**	**86.84**	**7.43**	**92.15**	**7.85**
SD	**4.41**	**4.66**	**3.67**	**1.40**	**1.52**	**2.15**	**2.87**	**2.95**	**2.95**

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood, textile and rubber

Table C.16 The sample weight for carbon and HHV analysis

Number of sample	The average value of sample weight for carbon analysis (mg)					The average value of sample weight for HHV analysis (g)				
	Food waste	Plastic	Paper	Wood	Textile	Food waste	Plastic	Paper	Wood	Textile
1	2.08	1.06	2.22	2.25	-	1.3602	0.5348	1.3405	1.2139	-
2	2.02	1.05	2.37	2.33	-	1.2450	0.5117	1.4447	1.2528	-
3	2.08	1.04	2.24	2.22	2.06	1.3401	0.4737	1.3788	1.2124	1.3525
4	2.08	1.04	2.24	2.22	2.06	1.3744	0.4637	1.4042	1.2852	1.2904
5	2.10	1.07	2.20	2.24	2.15	1.2696	0.4747	1.3824	1.2900	1.2566
6	2.08	1.07	2.21	2.25	2.15	1.2293	0.4790	1.3639	1.2329	1.2778
7	2.10	1.07	2.20	2.23	2.15	1.2885	0.5317	1.4275	1.2942	1.2721
average	**2.08**	**1.06**	**2.24**	**2.25**	**2.11**	**1.3010**	**0.4956**	**1.3917**	**1.2545**	**1.2899**
SD	**0.03**	**0.01**	**0.06**	**0.04**	**0.05**	**0.0575**	**0.0297**	**0.0363**	**0.0358**	**0.0371**

Table C.17 Ultimate analysis of food waste (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
Fw 1	12.34	10.03	75.35	0.52	0.06	1.70	100	38.93	7.53	46.36	1.63	0.19	5.36	100	42.94	7.15	41.99	1.80	0.21	5.91	100	44.00	45.64	7.60	44.63	1.92	0.22	100
Fw 2	10.07	10.37	78.27	0.44	0.03	0.82	100	35.61	8.30	51.52	1.55	0.11	2.91	100	40.56	7.89	46.34	1.77	0.13	3.31	100	48.24	41.95	8.16	47.93	1.83	0.13	100
Fw 3	9.19	10.22	78.16	0.53	0.04	1.87	100	38.22	7.14	44.51	2.19	0.15	7.79	100	42.94	6.64	39.03	2.46	0.17	8.75	100	41.67	47.06	7.28	42.77	2.70	0.19	100
Fw 4	7.21	10.49	80.56	0.32	0.03	1.39	100	35.45	7.74	48.21	1.59	0.15	6.86	100	40.28	7.27	42.69	1.81	0.17	7.79	100	44.66	43.68	7.88	46.29	1.96	0.18	100
Fw 5	7.31	10.42	80.26	0.27	0.03	1.72	100	37.85	7.18	44.51	1.39	0.16	8.90	100	42.10	6.73	39.54	1.55	0.18	9.90	100	41.27	46.73	7.47	43.88	1.72	0.20	100
Fw 6	10.42	9.62	73.34	0.58	0.07	5.97	100	35.45	5.85	36.19	1.98	0.23	20.30	100	38.54	5.38	31.61	2.15	0.25	22.07	100	34.01	49.45	6.90	40.57	2.75	0.32	100
Fw 7	12.28	9.56	72.25	1.25	0.16	4.50	100	37.45	6.21	38.31	3.82	0.48	13.73	100	40.70	5.78	33.93	4.15	0.52	14.92	100	38.60	47.84	6.79	39.88	4.88	0.61	100
Ave.	**9.83**	**10.10**	**76.88**	**0.56**	**0.06**	**2.57**	**100**	**36.99**	**7.14**	**44.23**	**2.02**	**0.21**	**9.41**	**100**	**41.15**	**6.69**	**39.31**	**2.24**	**0.23**	**10.38**	**100**	**41.78**	**46.05**	**7.44**	**43.71**	**2.54**	**0.27**	**100**
SD	**2.09**	**0.38**	**3.29**	**0.33**	**0.05**	**1.90**		**1.46**	**0.86**	**5.38**	**0.84**	**0.12**	**5.85**		**1.60**	**0.87**	**5.10**	**0.89**	**0.13**	**6.28**		**4.58**	**2.54**	**0.49**	**2.91**	**1.11**	**0.16**	

Remark: $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.18 Ultimate analysis of plastic (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
P 1	30.96	8.83	59.54	0.04	0.02	0.62	100	75.54	5.42	17.38	0.09	0.05	1.52	100	75.87	5.39	17.07	0.09	0.05	1.53	100	17.21	77.05	5.47	17.34	0.09	0.05	100
P 2	43.81	7.15	44.67	0.10	0.04	4.23	100	74.01	4.36	14.25	0.17	0.06	7.15	100	74.64	4.30	13.62	0.17	0.06	7.21	100	13.85	80.44	4.63	14.68	0.19	0.06	100
P 3	35.84	8.08	51.56	0.07	0.02	4.42	100	68.61	5.24	17.51	0.14	0.03	8.47	100	69.82	5.13	16.25	0.14	0.03	8.62	100	16.43	76.41	5.62	17.79	0.16	0.03	100
P 4	58.06	6.36	33.91	0.22	0.13	1.31	100	77.59	4.74	15.46	0.30	0.17	1.75	100	78.23	4.69	14.86	0.30	0.17	1.76	100	15.32	79.63	4.78	15.12	0.30	0.17	100
P 5	43.69	7.20	44.15	0.10	0.04	4.82	100	72.28	4.60	14.93	0.16	0.07	7.97	100	72.76	4.56	14.43	0.16	0.07	8.02	100	14.66	79.10	4.95	15.69	0.18	0.07	100
P 6	57.08	6.25	34.62	0.08	0.09	1.88	100	78.20	4.42	14.56	0.11	0.12	2.58	100	79.05	4.35	13.76	0.11	0.12	2.61	100	13.99	81.17	4.46	14.13	0.12	0.12	100
P 7	41.22	7.81	47.84	0.11	0.19	2.82	100	72.41	5.25	16.86	0.20	0.33	4.96	100	72.72	5.22	16.54	0.20	0.33	4.98	100	17.08	76.53	5.50	17.41	0.21	0.35	100
Ave.	**44.38**	**7.38**	**45.18**	**0.10**	**0.08**	**2.87**	**100**	**74.09**	**4.86**	**15.85**	**0.17**	**0.12**	**4.91**	**100**	**74.73**	**4.81**	**15.22**	**0.17**	**0.12**	**4.96**	**100**	**15.51**	**78.62**	**5.06**	**16.02**	**0.18**	**0.12**	**100**
SD	**10.10**	**0.93**	**9.07**	**0.06**	**0.06**	**1.66**		**3.35**	**0.44**	**1.37**	**0.07**	**0.10**	**3.00**		**3.27**	**0.44**	**1.40**	**0.07**	**0.10**	**3.04**		**1.42**	**1.95**	**0.47**	**1.48**	**0.07**	**0.11**	

Remark: $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.19 Ultimate analysis of paper (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
PP 1	17.89	8.51	65.98	0.09	0.03	7.50	100	35.78	5.83	43.14	0.18	0.07	15.00	100	38.07	5.48	40.22	0.19	0.07	15.96	100	40.49	45.30	6.53	47.86	0.23	0.08	100
PP 2	21.38	8.79	67.03	0.20	0.05	2.55	100	32.15	7.58	56.07	0.30	0.07	3.83	100	34.43	7.33	53.74	0.32	0.08	4.10	100	54.14	35.90	7.64	56.03	0.34	0.09	100
PP 3	26.62	7.46	56.64	0.22	0.03	9.02	100	35.61	6.20	45.80	0.29	0.04	12.07	100	37.98	5.86	42.94	0.31	0.04	12.87	100	43.29	43.59	6.72	49.28	0.36	0.05	100
PP 4	25.01	7.83	59.58	0.10	0.12	7.37	100	34.34	6.57	48.68	0.14	0.16	10.12	100	37.00	6.21	45.56	0.15	0.17	10.90	100	45.89	41.53	6.97	51.14	0.17	0.19	100
PP 5	19.32	7.63	59.05	0.07	0.04	13.90	100	34.42	4.84	35.79	0.12	0.07	24.76	100	36.22	4.50	33.02	0.13	0.07	26.06	100	33.22	48.99	6.09	44.66	0.17	0.09	100
PP 6	20.70	8.18	63.00	0.10	0.04	7.98	100	34.79	6.13	45.43	0.17	0.06	13.42	100	37.26	5.78	42.35	0.18	0.06	14.37	100	42.59	43.51	6.74	49.46	0.21	0.07	100
PP 7	28.10	5.85	44.26	0.16	0.05	21.58	100	33.40	4.84	35.86	0.19	0.06	25.65	100	35.32	4.48	32.82	0.20	0.06	27.12	100	33.08	48.46	6.14	45.04	0.27	0.08	100
Ave.	**22.72**	**7.75**	**59.36**	**0.13**	**0.05**	**9.99**	**100**	**34.36**	**6.00**	**44.40**	**0.20**	**0.08**	**14.98**	**100**	**36.61**	**5.66**	**41.52**	**0.21**	**0.08**	**15.91**	**100**	**41.81**	**43.90**	**6.69**	**49.07**	**0.25**	**0.10**	**100**
SD	**3.88**	**0.96**	**7.65**	**0.06**	**0.03**	**6.10**		**1.26**	**0.97**	**7.14**	**0.07**	**0.04**	**7.84**		**1.36**	**0.99**	**7.28**	**0.08**	**0.04**	**8.21**		**7.34**	**4.44**	**0.53**	**3.88**	**0.08**	**0.05**	

Remark: $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.20 Ultimate analysis of wood (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
W 1	16.82	9.45	72.66	0.09	0.05	0.93	100	37.77	7.29	52.52	0.20	0.12	2.10	100	40.72	6.98	49.69	0.21	0.13	2.26	100	50.04	41.66	7.14	50.84	0.22	0.14	100
W 2	28.01	8.33	62.14	0.14	0.06	1.32	100	37.32	7.38	53.28	0.19	0.08	1.76	100	40.73	7.03	50.02	0.21	0.09	1.92	100	50.32	41.53	7.17	51.00	0.21	0.09	100
W 3	27.13	8.31	62.22	0.13	0.06	2.15	100	37.00	7.26	52.55	0.18	0.08	2.93	100	40.77	6.86	48.85	0.20	0.09	3.23	100	49.14	42.13	7.09	50.48	0.21	0.09	100
W 4	26.68	8.44	63.39	0.10	0.06	1.34	100	38.60	7.21	52.02	0.15	0.08	1.94	100	42.14	6.84	48.65	0.16	0.09	2.12	100	48.90	43.05	6.98	49.71	0.16	0.09	100
W 5	36.30	7.46	54.30	0.17	0.06	1.70	100	38.57	7.23	52.15	0.18	0.06	1.81	100	41.67	6.91	49.20	0.19	0.06	1.96	100	49.46	42.50	7.05	50.18	0.20	0.06	100
W 6	33.37	7.68	56.33	0.09	0.06	2.46	100	37.31	7.27	52.49	0.10	0.07	2.75	100	40.41	6.95	49.47	0.11	0.08	2.98	100	49.66	41.65	7.16	50.99	0.12	0.08	100
W 7	35.66	7.02	51.38	0.39	0.11	5.44	100	38.23	6.72	48.67	0.42	0.12	5.83	100	41.96	6.29	44.76	0.46	0.13	6.40	100	45.35	44.83	6.72	47.82	0.50	0.14	100
Ave.	**29.14**	**8.10**	**60.35**	**0.16**	**0.07**	**2.19**	**100**	**37.83**	**7.19**	**51.95**	**0.20**	**0.09**	**2.73**	**100**	**41.20**	**6.84**	**48.66**	**0.22**	**0.10**	**2.98**	**100**	**48.98**	**42.48**	**7.05**	**50.15**	**0.23**	**0.10**	**100**
SD	**6.77**	**0.79**	**7.08**	**0.11**	**0.02**	**1.52**		**0.65**	**0.22**	**1.50**	**0.10**	**0.02**	**1.44**		**0.70**	**0.25**	**1.78**	**0.11**	**0.03**	**1.59**		**1.67**	**1.17**	**0.16**	**1.13**	**0.12**	**0.03**	

Remark: $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.21 Ultimate analysis of textile (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
T 1	27.61	9.66	60.71	0.43	0.05	1.55	100	46.12	8.63	41.85	0.71	0.09	2.59	100	47.49	8.57	40.52	0.73	0.09	2.67	100	41.27	48.76	8.80	41.60	0.75	0.09	100
T 2	29.45	9.73	59.14	0.44	0.03	1.21	100	45.45	8.94	43.03	0.68	0.05	1.86	100	46.45	8.90	42.07	0.69	0.05	1.90	100	42.75	47.32	9.07	42.86	0.71	0.05	100
T 3	32.77	10.22	54.86	0.30	0.03	1.82	100	38.08	10.06	49.36	0.35	0.04	2.11	100	40.14	10.01	47.30	0.37	0.04	2.22	100	47.63	41.02	10.22	48.33	0.38	0.04	100
T 4	26.63	9.31	56.78	0.39	0.15	6.74	100	38.09	8.50	43.00	0.56	0.22	9.64	100	41.38	8.27	39.09	0.61	0.24	10.47	100	39.88	46.19	9.23	43.63	0.68	0.27	100
T 5	22.04	9.70	63.45	1.16	0.17	3.49	100	40.77	8.43	41.91	2.14	0.31	6.45	100	43.30	8.26	39.05	2.27	0.33	6.85	100	41.59	46.45	8.86	41.89	2.44	0.36	100
Ave.	**27.70**	**9.72**	**58.99**	**0.54**	**0.09**	**2.96**	**100**	**41.70**	**8.91**	**43.83**	**0.89**	**0.14**	**4.53**	**100**	**43.75**	**8.80**	**41.61**	**0.93**	**0.15**	**4.82**	**100**	**42.62**	**45.95**	**9.24**	**43.66**	**0.99**	**0.16**	**100**
SD	**3.94**	**0.32**	**3.35**	**0.35**	**0.07**	**2.29**		**3.89**	**0.67**	**3.14**	**0.71**	**0.12**	**3.41**		**3.17**	**0.72**	**3.42**	**0.76**	**0.13**	**3.74**		**2.98**	**2.93**	**0.58**	**2.73**	**0.82**	**0.14**	

Remark: $O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.22 Ultimate analysis of combustible MSW (except rubber) (as received basis, air dry basis, dry basis and dry and ash free basis)

No.	(%) as received basis							(%) air dry basis							(%) dry basis								(%) dry and ash free basis					
	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	C	H	O	N	S	A	Total	O*	C	H	O	N	S	Total
C 1	15.91	9.74	72.15	0.41	0.05	1.75	100	46.24	6.97	40.35	1.19	0.15	5.09	100	49.84	6.65	36.58	1.27	0.17	5.49	100	38.02	52.74	7.04	38.71	1.34	0.17	100
C 2	18.08	9.58	70.34	0.35	0.03	1.62	100	48.25	6.89	39.51	0.93	0.09	4.33	100	52.35	6.52	35.32	1.02	0.10	4.69	100	36.44	54.93	6.84	37.06	1.07	0.10	100
C 3	17.45	9.48	69.74	0.39	0.04	2.90	100	48.93	6.40	35.37	1.08	0.09	8.14	100	52.49	6.05	31.47	1.16	0.10	8.73	100	32.73	57.51	6.63	34.48	1.27	0.11	100
C 4	23.44	9.13	65.42	0.28	0.06	1.66	100	58.68	6.04	30.28	0.71	0.16	4.15	100	61.83	5.76	27.14	0.75	0.17	4.37	100	28.04	64.64	6.02	28.37	0.78	0.18	100
C 5	21.88	9.01	65.17	0.19	0.04	3.71	100	55.50	5.66	28.84	0.49	0.09	9.42	100	57.98	5.42	26.17	0.51	0.10	9.83	100	26.77	64.29	6.01	29.02	0.57	0.11	100
C 6	27.40	8.39	59.13	0.38	0.08	4.62	100	58.50	5.21	25.45	0.82	0.16	9.87	100	61.07	4.94	22.66	0.86	0.17	10.31	100	23.68	68.08	5.51	25.26	0.96	0.19	100
C 7	22.47	8.80	62.91	0.83	0.16	4.82	100	51.34	5.73	29.65	1.90	0.37	11.02	100	53.85	5.46	26.76	1.99	0.38	11.55	100	29.14	60.89	6.18	30.26	2.24	0.43	100
Ave.	**20.95**	**9.16**	**66.41**	**0.40**	**0.07**	**3.01**	**100**	**52.49**	**6.13**	**32.78**	**1.02**	**0.16**	**7.43**	**100**	**55.63**	**5.83**	**29.44**	**1.08**	**0.17**	**7.85**	**100**	**30.69**	**60.44**	**6.32**	**31.88**	**1.18**	**0.18**	**100**
SD	**4.02**	**0.48**	**4.60**	**0.20**	**0.04**	**1.40**		**5.07**	**0.66**	**5.70**	**0.45**	**0.10**	**2.86**		**4.67**	**0.62**	**5.14**	**0.47**	**0.10**	**2.95**		**5.24**	**5.62**	**0.54**	**4.95**	**0.54**	**0.11**	

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

$O_{db}^{*} = 100 - C_{db} - H_{db} - A_{db}$

Table C.23 The average value and SD of residual moisture, hydrogen, HHV and LHV of food waste

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Food waste 1	4446	7.15	4078	9.33	4031
Food waste 2	4446	7.89	4040	12.20	3904
Food waste 3	4856	6.64	4514	11.00	4322
Food waste 4	4226	7.27	3851	11.97	3720
Food waste 5	4407	6.73	4060	10.10	3962
Food waste 6	3693	5.38	3416	8.02	3397
Food waste 7	4207	5.78	3909	7.98	3871
average	**4326**	**6.69**	**3981**	**10.09**	**3887**
SD	**351**	**0.87**	**328**	**1.74**	**284**

Table C.24 The average value and SD of residual moisture, hydrogen, HHV and LHV of plastic

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Plastic 1	10712	5.39	10434	0.44	10665
Plastic 2	9859	4.30	9637	0.85	9775
Plastic 3	9689	5.13	9425	1.74	9520
Plastic 4	10279	4.69	10037	0.81	10196
Plastic 5	8875	4.56	8640	0.67	8816
Plastic 6	10424	4.35	10200	1.07	10312
Plastic 7	9417	5.22	9148	0.44	9376
average	**9894**	**4.81**	**9646**	**0.86**	**9809**
SD	**633**	**0.44**	**631**	**0.45**	**632**

Table C.25 The average value and SD of residual moisture, hydrogen, HHV and LHV of paper

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Paper 1	3799	5.48	3517	6.02	3570
Paper 2	3749	7.33	3371	6.63	3500
Paper 3	3859	5.86	3557	6.25	3618
Paper 4	3729	6.21	3409	7.20	3461
Paper 5	3404	4.50	3172	4.97	3235
Paper 6	3753	5.78	3455	6.63	3504
Paper 7	3279	4.48	3048	5.43	3101
average	**3653**	**5.66**	**3361**	**6.16**	**3427**
SD	**220**	**0.99**	**186**	**0.76**	**188**

Table C.26 The average value and SD of residual moisture, hydrogen, HHV and LHV of wood

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Wood 1	4458	6.98	4098	7.25	4135
Wood 2	4537	7.03	4175	8.38	4157
Wood 3	4500	6.86	4147	9.26	4083
Wood 4	4580	6.84	4228	8.40	4195
Wood 5	4634	6.91	4278	7.44	4289
Wood 6	4534	6.95	4176	7.63	4188
Wood 7	4543	6.29	4219	8.88	4140
average	**4541**	**6.84**	**4189**	**8.18**	**4170**
SD	**56**	**0.25**	**59**	**0.76**	**65**

Table C.27 The average value and SD of residual moisture, hydrogen, HHV and LHV of textile

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Textile 1	4955	8.57	4514	2.89	4812
Textile 2	5043	8.90	4584	2.12	4936
Textile 3	4043	10.01	3527	5.07	3838
Textile 4	4400	8.27	3974	7.9	4052
Textile 5	4375	8.26	3949	5.79	4122
average	**4563**	**8.80**	**4110**	**4.75**	**4352**
SD	**423**	**0.72**	**439**	**2.32**	**490**

Table C.28 The average value and SD of residual moisture, hydrogen, HHV and LHV of combustible MSW

Number of sample	HHV from measurement, cal/g (db)	H (% db)	LHV from calculation, cal/g (db)	Residual moisture (% ad)	HHV from calculation, cal/g (ad)
Combustible MSW 1	5792	6.65	5449	7.23	5373
Combustible MSW 2	6342	6.52	6006	7.84	5845
Combustible MSW 3	6541	6.05	6229	6.80	6096
Combustible MSW 4	7660	5.76	7363	5.10	7269
Combustible MSW 5	6723	5.42	6444	4.26	6437
Combustible MSW 6	7462	4.94	7208	4.22	7147
Combustible MSW 7	6341	5.46	6060	4.66	6046
average	**6694**	**5.83**	**6394**	**5.73**	**6316**
SD	**659**	**0.62**	**681**	**1.52**	**689**

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

Table C.29 The heating value of food waste and plastic calculated by using Hess's law

No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)	No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)
Food waste 1	-974	-6174	-4446	-701	-273	-1728	Plastic 1	-739	-7906	-10712	-1001	262	2806
Food waste 2	-1043	-6074	-4446	-763	-279	-1628	Plastic 2	-706	-7886	-9859	-882	177	1973
Food waste 3	-945	-6176	-4856	-743	-202	-1320	Plastic 3	-745	-7904	-9689	-913	168	1785
Food waste 4	-1008	-6116	-4226	-697	-312	-1890	Plastic 4	-712	-7872	-10279	-929	218	2407
Food waste 5	-958	-6215	-4407	-679	-279	-1808	Plastic 5	-718	-7890	-8875	-808	90	985
Food waste 6	-908	-6239	-3693	-538	-371	-2546	Plastic 6	-699	-7885	-10424	-925	225	2539
Food waste 7	-915	-6079	-4207	-633	-282	-1872	Plastic 7	-741	-7881	-9417	-886	145	1536
average	-964	-6153	-4326	-679	-285	-1827	average	-723	-7889	-9894	-906	183	2004
SD	49	65	351	75	50	372	SD	19	12	633	59	57	632

Table C.30 The heating value of paper and wood calculated by using Hess's law

No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)	No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)
Paper 1	-919	-5779	-3799	-604	-315	-1980	Wood 1	-986	-5706	-4458	-770	-216	-1248
Paper 2	-1088	-5423	-3749	-752	-336	-1674	Wood 2	-989	-5702	-4537	-787	-202	-1165
Paper 3	-943	-5710	-3859	-637	-306	-1851	Wood 3	-978	-5724	-4500	-769	-209	-1224
Paper 4	-978	-5638	-3729	-647	-331	-1909	Wood 4	-963	-5759	-4580	-766	-197	-1179
Paper 5	-870	-5919	-3404	-500	-370	-2515	Wood 5	-972	-5739	-4634	-785	-187	-1105
Paper 6	-945	-5713	-3753	-621	-324	-1960	Wood 6	-987	-5711	-4534	-784	-203	-1177
Paper 7	-876	-5895	-3279	-487	-389	-2616	Wood 7	-933	-5809	-4543	-730	-203	-1266
average	-945	-5725	-3653	-607	-339	-2072	average	-973	-5736	-4541	-770	-203	-1195
SD	74	167	220	91	30	353	SD	20	38	56	20	9	55

Table C.31 The heating value of textile and combustible MSW calculated by using Hess's law

No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)	No.	Heat of formation of products (kcal/mole)	Heat of formation of products (cal/g)	Heat of reaction (cal/g)	Heat of reaction (kcal/mole)	Heat of formation of reactants (kcal/mole)	Heat of formation of reactants (cal/g)
Textile 1	-1008	-6826	-4955	-732	-276	-1871	Combustible MSW 1	-893	-6538	-5792	-791	-102	-746
Textile 2	-1035	-6803	-5043	-767	-268	-1760	Combustible MSW 2	-871	-6641	-6342	-831	-39	-299
Textile 3	-1177	-6705	-4043	-710	-467	-2662	Combustible MSW 3	-848	-6771	-6541	-819	-29	-230
Textile 4	-1056	-6776	-4400	-686	-370	-2376	Combustible MSW 4	-793	-7124	-7660	-853	60	536
Textile 5	-1034	-6673	-4375	-678	-356	-2298	Combustible MSW 5	-794	-7091	-6723	-753	-41	-368
							Combustible MSW 6	-763	-7218	-7462	-789	26	244
							Combustible MSW 7	-814	-6887	-6341	-750	-65	-546
average	-1062	-6757	-4563	-715	-348	-2193	average	-825	-6896	-6694	-798	-27	-201
SD	66	65	423	36	81	373	SD	47	259	659	39	54	446

Remark: Combustible MSW = mixture of food waste, plastic, paper, wood and textile

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