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SOLID CHAR CHARACTERIZATION FROM EFFECT OF RADIATION TIME STUDY ON MICROWAVE ASSISTED PYROLYSIS OF KITCHEN WASTE

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Abstract

Increment of population in a country influenced the generation of high amount solid waste that being sent to the landfill. High proportions of solid waste were contributed by the kitchen / food waste. Currently, conventional method used for final disposal of these wastes was through landfilling or through direct incineration. However, high moisture content at 90% stretched a dilemma for both disposal method which leachate was generated from the landfill and furthermore, it cannot be achieved or limited by using incineration due to the humidity limitation of the incinerator. In this research, microwave assisted pyrolysis introduced was not only to dispose the waste, at the same time can recover valuable material from the kitchen waste. Effect of radiation time was studied at range 10 min to 60 min in the process in order to get optimum process condition. Meanwhile, other parameter such as microwave power level, sample weight loading and microwave absorber ratio were set constant at 1000W, 200g, and 20%wt/wt respectively. High conversion of kitchen waste was transformed into solid char was obtained at low radiation time with conversion >80%. Solid char obtained was analysed and had good fuel properties with calorific value >16000 J/kg. Solid char obtained also has high carbon content and low oxygen content which indicated the pyrolysis had fully transform the kitchen waste to carbon solid char and contained low hydrocarbon chemical content. In a nutshell, the microwave assisted pyrolysis can be implemented to treat the kitchen waste and at the same time can recover the valuable material which has the potential to become solid fuel.

Keywords: Solid char, Radiation time, Microwave assisted pyrolysis, Kitchen waste.

Nomenclatures

S_o	Initial weight of sample
S_f	Weight of solid char
$\%M$	Moisture percentage
$\%H$	Hydrogen percentage

Abbreviations

AC	Activated Carbon
C	Carbon
FTIR	Fourier Transform Infrared
GCV	Gross Calorific Value
H	Hydrogen
ICI	Industrial, Commercial and Institutional
N	Nitrogen
NCV	Net Calorific Value
O	Oxygen
S	Sulphur
XRF	X-ray Fluorescence

1. Introduction

Kitchen waste can be considered as the food scrap or food waste that is discarded and cannot be used. Examples of waste that comes from kitchen are rice, chicken, fish and leafy vegetables. Kitchen waste is one of the major contributions in the municipal solid waste generation. According to Malaysia National Solid Waste Management Authority, food waste is the highest contributor in solid waste generation compare to any other type of waste [1]. Every year, approximately 35 million tons of food waste will be sent to the landfills and incinerators for disposal in the country. Figure 1 shows the pie chart of Malaysia ICI waste composition in 2013. Aimed for this study is study the capability of microwave assisted pyrolysis process to convert kitchen waste into useable materials like solid char.

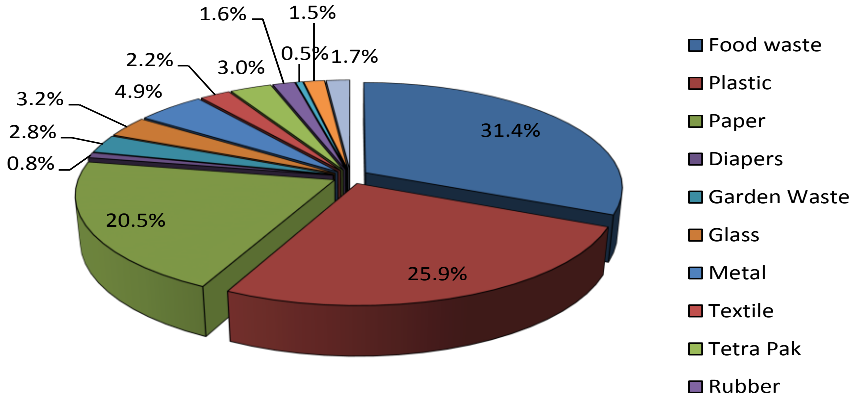

Fig. 1. Malaysia ICI Waste Composition, 2013 [1].

2. Background Study

2.1. Characteristic of kitchen waste

The major sources of the kitchen waste are usually associated with cooking and food preparation. Kitchen waste contains lots of rich nutrients which including carbohydrates, proteins and fibre that are not harmful. These nutrients are the major composition that usually found in the kitchen waste. The characteristics of the kitchen waste can divided into two which are physical characteristics and chemical characteristics. The Physical characteristics of the kitchen waste provides the information regarding to the physical condition of the waste such as moisture content, density, colour and size distribution of components that are found in the kitchen waste [2]. The major composition and physical characteristics of kitchen waste in Malaysia are shown in Table 1.

Table 1. Composition percentage of food waste on weight basis in Malaysia.

Components	**Composition (%)** [3]
Moisture	78.09
Ash	1.42
Total sugar	10.36
Carbohydrates	8.05
Protein	3.50
Fat	5.22
Fiber (cellulose, lignin, hemicellulose)	4.64

The moisture content shows the highest composition in kitchen waste. This is because; leachate is produced in the kitchen waste. Leachate is the liquid that extract solutes from other matters. In the kitchen waste, the waste will be decomposed by the bacterial present which leads to the formation of leachate. That cause the moisture content is so high in the kitchen waste. Chemical characteristics of the kitchen waste can be referred as the chemical constituents that present in the kitchen waste. Chemical characteristics of the kitchen waste include moisture, ash, volatile matter, percentage of carbon, hydrogen, oxygen, sulfur and ash, fixed carbon, calorific value and fusing point of ash. These chemical properties can be analysed by using proximate and ultimate analysis. Table 2 below shows the proximate analysis for the kitchen waste. The data was taken from the proximate analysis of collected sample at Bakri Landfill, Muar, Malaysia [4].

Table 2. Proximate analysis of food waste [4].

Components	**Composition (%)**
Moisture content (% by weight)	75-82
Moisture content	30.7-33.5
Ash content	14.0
Volatile matter	80.0
Fixed carbon	6.0

2.2. Conventional treatment to recover kitchen waste

There are many conventional methods and treatments to treat the kitchen waste as shown in Table 3. However, there is no further study about the microwave pyrolysis of the kitchen waste. Although pyrolysis is still under development in the waste industry, this process has received special attention, not only as a primary process of combustion and gasification, but also as independent process leading to the production of energy-dense products with numerous uses. This makes the pyrolysis treatment process self-sufficient in terms of energy use, and also significantly reduces operating costs.

Table 3. Convention treatment to recover the kitchen waste

Method/ Treatment	Recover	Details	Reference
Separate hydrolysis and fermentation (SHF) process	Ethanol	Kitchen waste is collected and undergoes open fermentation process. After that, distillery process takes place to produce ethanol.	[5]
Composting	Fertilizer	Home composting or in-vessel composting facility whereby the compost product can be used as fertilizers or soil amendments.	[6, 7]
Wet feeding	Animal feed	Facility that process and convert the kitchen waste into the safe animal feeds	[7]
Anaerobic digestion	Methane and biogas	The food waste is collected at urban residential area and undergoes anaerobic digestion process. From this process, about 65% methane is produced with an energy content of 6.25 kWh/m^3 of biogas.	[8]
Incineration	Energy sources like steam for power plant	Collected organic food waste will enter incinerator and undergo combustion process to produce steam for electricity generation in power plant.	[9]

2.3. Microwave pyrolysis as a potential treatment method for kitchen waste generation

Heating mechanism during pyrolysis is not only limited to electrical heating, gas burning, or fuel heating mechanism; it has been improvised by introducing the microwave irradiation to the sample which in turn, beam of microwave wavelength to the sample excited the molecule that has high dielectric constant to self-propagate, then it converts the motion energy resulted from sample self-propagation into heat energy [10]. This phenomenon was called Ionic Conduction [11]. Implementation of microwave irradiation into the pyrolysis reaction reduced the radiation time. In fact, treatment of kitchen waste with pyrolysis via microwave radiation is an alternative treatment for disposal of these wastes with high moisture content. This is due to the high affinity of water content leads to the high amount of dielectric constant which enhanced the atomic self- propagation of water molecule. In addition, it is necessary to dry off high amount of water from sample before pyrolysis process because conventional pyrolysis requires longer radiation time. Thus microwave heating serve as an alternative method for drying, pyrolyzing and gasifying high moisture materials in one single step. It is a huge advantage of microwave assisted pyrolysis process which can reduced the radiation time required in conventional heating method [12, 13]. In addition, effect of additional material with high dielectric constant at 18.8 such as activated carbon (AC) also been studied. With the additional of activated carbon to the kitchen waste, it could increase the overall dielectric constant of kitchen waste. Dielectric properties of water and high moisture content in the food or kitchen waste is high due to the dipolar rotation [14]. Microwave assisted pyrolysis of material by using microwave absorbance has been practices by several researchers in recent time. Purpose of this attempt due to the optimization of several factors that influenced the process such as increment of product yield, optimum chemical breakdown, the usage of carrier gas, reduce the thermal degradation temperature, reduction of radiation time, and reduction of microwave power level used. It has been reported that, the usage of microwave absorbance such as coal/char on the palm kernel shell affected its thermal degradation [15]. It is an advantage to expand the research on the kitchen waste by using this technique since it’s not been investigate yet in any research.

3. Materials and Methods

3.1. Material preparation

The kitchen waste was collected and kept in the seal plastic bag. After that, the collected sample was kept in the refrigerator at the laboratory to make sure the sample is well preserved and not easily rotten and contaminate. The samples were then weighted with constant mass loading for 200g for each run of the experiment. The experiment was run for two sets. One set was added with absorbent at 20 wt% of activated carbon (AC) while the other set was without any absorbent. After that, the samples were inserted into the microwave pyrolysis equipment.

3.2. Microwave assisted pyrolysis equipment

Microwave assisted pyrolysis equipment use in this research was adopted from previous research [16]. Set of raw materials were inserted in the quartz reactor and the arrangement of the equipment was shown in Fig. 2. Nitrogen gas was purged in the preliminary experiment at 200 ml/min in order to remove the oxygen due to the pyrolysis condition that necessarily required the absence of oxygen. Upon the main experiment, 100 ml/min of nitrogen gas was used along the experiment. Microwave power level was set constant at 1000W according to the best condition from previous experiment [17]. Radiation time was manipulated at range of 10, 20, 30, 40, 50 and 60 min. Solid char obtained was analyzed to determine its properties and compare to the conventional solid char that use as solid fuel.

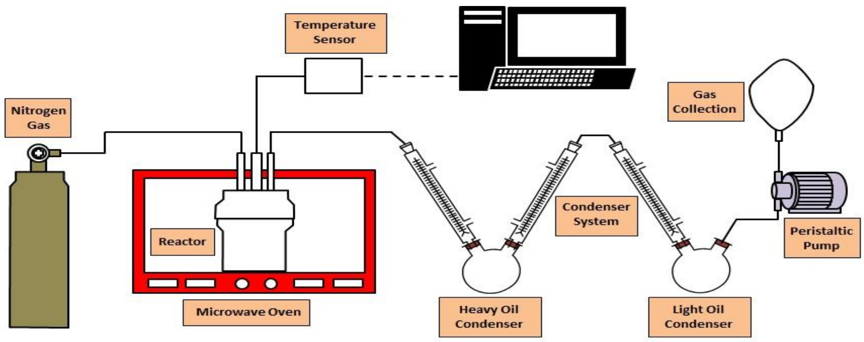

Fig. 2. Schematic diagram for microwave pyrolysis system ([17].

3.3. Analysis of the product

Product yields from the experiment were analyzed in order to determine fraction of product obtained such as solid char, liquid oil and syn gas. Nevertheless, only solid product was deeply analyzed in this research paper. Perfect pyrolysis was determined by analyzed the conversion of solid product as shown in the Eq. (1) where S_o is the initial weight of sample and S_f is the weight of solid char [18].

$$\boldsymbol{Conversion}\ (\%) = \frac{\boldsymbol{S_o - S}}{\boldsymbol{S_o}}\ \boldsymbol{x\ 100}$$
(1)

Energy content of solid products was analyzed by using Bomb calorimeter model IKA WORKS/C5000 Control Germany D79019. Carbon, hydrogen, nitrogen, sulfurs and oxygen content of product was analyzed by using Elemental Analyzer, Thermo Electron, Flash EA 1112 Series. All the chemical bonding like double bond and triple bond are determined by using FTIR spectroscopy, FTIR Perkin Elmer Spectrum 1. Thus, the existence of the hydrocarbon inside the solid and liquid products obtained can be determined. The inorganic content analysis of solid char has been analyzed by using XRF, X-Ray Fluorescence Spectrometer. About 1 gram of sample has been used in the analysis. Sample been compressed into pellet by using 2 tons sample compressor press before it has been analyzed. High intensity of X-Ray wavelength is used to detect the inorganic compound presence in the kitchen waste solid char.

4. Results and Discussion

4.1. Product yields

Based on the pyrolysis of the kitchen waste via microwave assisted pyrolysis, three products were formed which are solid char, condensed liquid and uncondensed gas. The results of the experiment were compared based on the effect of radiation time and also the percentage yield from non-microwave absorber and microwave absorber reaction of activated carbon with kitchen waste. Based from Fig. 3, addition of small amount of activated carbon gave significant effect of the product yields for the microwave assisted pyrolysis of kitchen waste. From the radiation time range between 10 minutes to 60 minutes, it has been observed that the addition of activated carbon as the microwave absorber significantly affects the percentage yields of the condensed liquid. At radiation time 60 minute and without mixing the activated carbon heterogeneously with the kitchen waste, the percentage of condensed liquid at 25.45%. However, when the kitchen waste is mixed with the activated carbon heterogeneously, the percentage of condensed liquid can be achieved up to 46.25% at radiation time 60 minute. The increment of the percentage condensed liquid was observed to be about 45% when mixing the kitchen waste heterogeneously with the activated carbon. The increments of the liquid product lead to the increment for the solid product conversion.

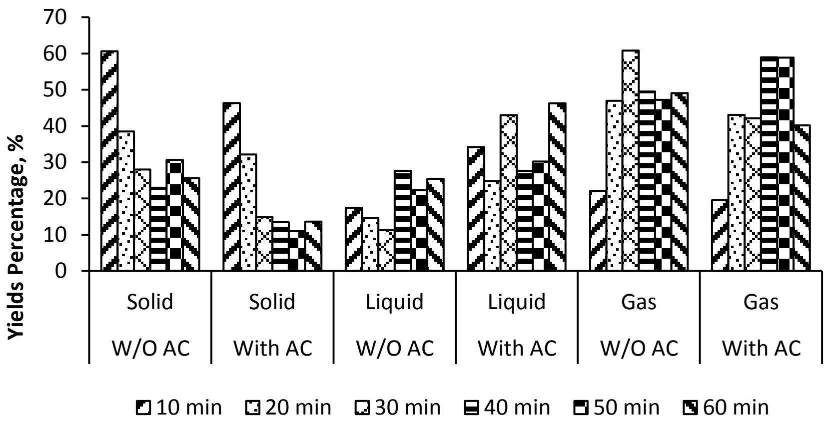

Fig. 3. Yield percentage of product distribution at 1000 W during microwave pyrolysis.

Conversion of kitchen waste with the present of activated carbon as the microwave absorbance is shown in Fig. 4. Calculation for conversion of solid product for microwave absorber reaction was done after deduct the proportion of activated carbon remained in the solid residue. Conversion percentage of kitchen waste was increased proportionally to the increment of radiation time for both with the addition of microwave absorber and without the microwave absorber respectively. Highest conversion was recorded on the microwave assisted pyrolysis of the kitchen waste with the additional of microwave absorber at radiation time 50 minute with conversion at 89.0%. However, compare to the without the additional of microwave absorber, the highest conversion only recorded at 74.65% with radiation time 40 minute. The increment of this conversion is about 16% which is quiet high. It seems the formation of char was started to form at radiation time 30 minutes for the microwave assisted pyrolysis of kitchen waste with the addition of microwave absorber as shown in Table 4. However, the formation of char for microwave assisted pyrolysis of kitchen waste with the absence of microwave absorber was started to form at radiation time 40 minutes. This is due to the addition of microwave absorber can shorter the reaction time during microwave pyrolysis reaction of the kitchen waste. Figure 4 below shows the comparison of solid conversion for the microwave assisted pyrolysis of the kitchen waste between the presence and absence of microwave absorber respectively.

Table 4. Conversion of solid product.

Microwave Absorber	Radiation Time (min)	Conversion (%)	Form
Without Activated Carbon	10	39.45	Undried sample
	20	47.25	Dried sample
	30	72.05	Semi coke
	40	74.45	Char
	50	69.40	Char
	60	74.65	Char
With Activated Carbon	10	53.65	Undried sample
	20	67.85	Semi coke
	30	85.05	Char
	40	86.55	Char
	50	89.00	Char
	60	86.40	Char

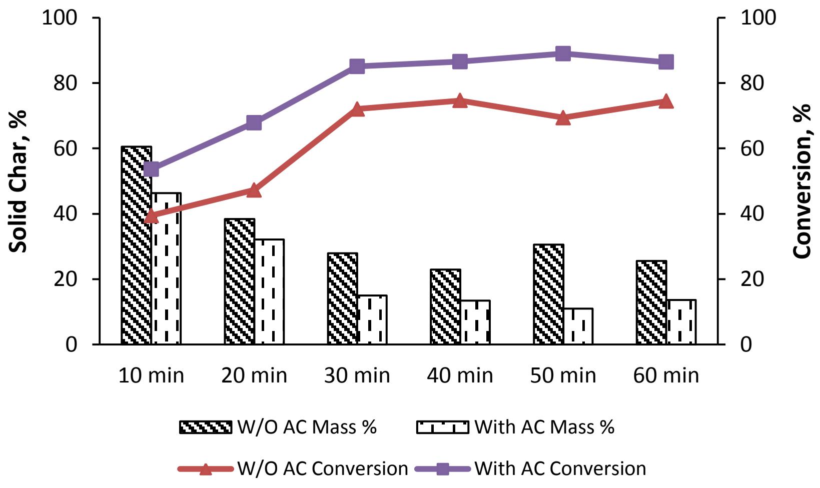

Fig. 4. Solid char formation and conversion from microwave assisted pyrolysis of kitchen waste.

4.2. Energy content analysis

By observing to Fig. 5, the additional of activated carbon to the kitchen waste during microwave pyrolysis only has slightly increased in the Gross Calorific Value (GCV) at 18,689 J/g compared to the solid product from pyrolysis of kitchen waste sample without activated carbon at 16,750 J/g. Besides that, it can be observed that as the radiation time increase, the energy content within the sample for both with and without microwave absorber also increased. This is because, as the radiation time keep increasing, this will lead to the complete pyrolysis of the kitchen waste sample whereby the sample is kept exposed to the penetration of microwave length which will remove the water molecule content in the sample. Thus, this will increase the energy content in the sample. Net calorific value which showed the net value of energy content without the presence of water or moisture is calculated according to Dulong's formula as shown in Eq. (2) and the value of NCV is showed in Table 5;

Net Calorific Value,

$$\text{NCV, J/g} = \text{Gross Calorific Value (GCV)} - 24.44\ (9\%\text{H} + \%\text{M}) \qquad (2)$$

Based on Fig. 5, additional of activated carbon as microwave absorber was enhanced the microwave assisted pyrolysis process especially for kitchen waste sample. It increased the radiation temperature during the microwave pyrolysis process, acts as heating medium, and promoted the moisture removal and increased the performance of solid char obtained after microwave pyrolysis process. Therefore, this will cause the energy content in the sample that is mixed with the microwave absorber slightly higher compare to the sample that is not mixed with the microwave absorber.

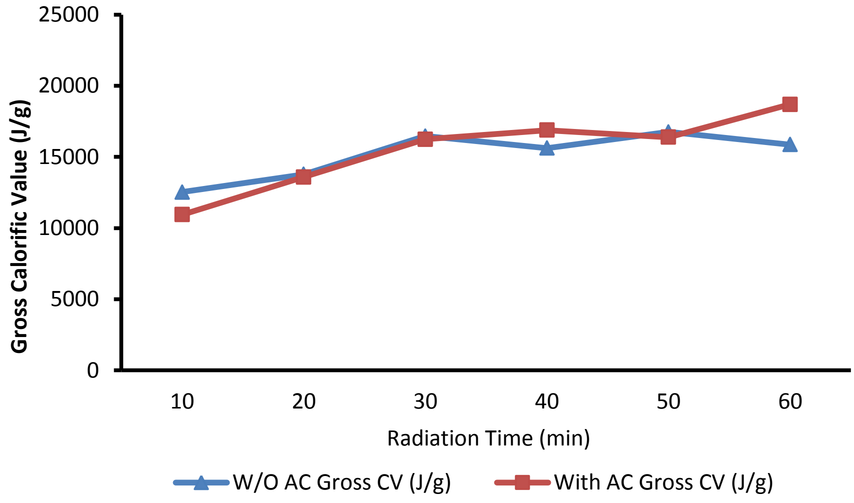

Fig. 5. Gross calorific value of solid products.

4.3. Ultimate analysis of solid product

In order to determine the major elements content in the sample like carbon, hydrogen, nitrogen, sulphur and oxygen, elemental analyser is used for the analysis. The purpose for this analysis is to compare with the C, H, N, S, O of solid fuel like coal with the solid char that is obtained after the microwave-assisted pyrolysis process of the kitchen waste. The conventional coal like lignite consists of element, C≈ 63.09%, H≈ 4.17%, N≈ 0.96%, S≈ 0.33% and O≈ 16.67% while bituminous coal consist of element, C≈ 70.13%, H≈ 385 4.64%, N≈ 1.5%, S≈ 0.44% and O≈ 11.36%. Based from Table 6, it shows the overall ultimate analysis of the solid product. It is observed that the highest conversion of solid char formation take place at radiation time 60 minutes for non-microwave absorbance and 50 minutes for microwave absorbance which are 74.65% and 89% respectively.

Table. 5. GCV and NCV of solid products.

Microwave Absorber	Radiation Time (min)	GCV (J/g)	NCV (J/g)
Without Activated Carbon	10	12524	12512
	20	13778	13775
	30	16461	16456
	40	15621	15615
	50	16750	16737
	60	15865	15844
With Activated Carbon	10	10939	10934
	20	13586	13581
	30	16236	16213
	40	16878	16862
	50	16384	16371
	60	18689	18674

Table 6. Ultimate analysis of solid product.

Microwave Absorber	Radiation Time (min)	Elements (%)							
		C	H	N	S	O*	Ash	H/O	H/C
Without Activated Carbon	10	27.76	5.1391	2.3153	0	23.81	40.98	0.2158	0.1851
	20	28.94	0.8396	2.0422	0	32.32	35.85	0.0260	0.0290
	30	33.80	1.3515	2.3343	0	36.64	25.87	0.0369	0.0400
	40	36.97	2.1251	2.4169	0	34.85	23.64	0.0610	0.0575
	50	43.26	4.8739	3.8234	0	29.49	18.55	0.1653	0.1127
	60	46.72	4.5207	6.0544	0	29.25	13.45	0.1546	0.0968
With Activated Carbon	10	32.80	1.9021	2.2477	0	22.07	40.98	0.0862	0.0580
	20	41.25	1.874	3.9088	0	17.12	35.85	0.1095	0.0454
	30	42.31	7.657	5.6245	0	18.54	25.87	0.4130	0.1810
	40	44.32	6.8712	2.2096	0	22.96	23.64	0.3000	0.1550
	50	52.36	4.9602	3.4807	0	20.65	18.55	0.2402	0.0947
	60	52.90	6.0831	4.0007	0	23.57	13.45	0.2581	0.1150

*Calculated by difference
%O = 100 – (%C + %H + %N + %S + %Ash)

The carbon content for sample at radiation time 60 minutes for non-microwave absorber is 46.72% while the carbon content for sample at radiation time 50 minutes for microwave absorbance is 52.90%. Both carbon contents for the samples were considered quiet high compare to the carbon content in the conventional coal. This shows that the solid char product has the potential to become the source of solid fuel due to high carbon contents. Besides that, there is no trace of sulfur element in the solid products for both samples. This gives an advantage for the solid char of the kitchen waste to become source of solid fuel that not gives environmental pollution problem during the combustion process take place. Other than that, the oxygen content for sample at radiation time 60 minutes for non-microwave absorber is 29.25% while the oxygen content for sample at radiation time 50 minutes for microwave absorbance is 23.57%. This shows that the oxygen for both samples are slightly higher compare to the conventional coal which make the solid char has the potential to become source of solid fuel because oxygen content can support and initiate the combustion process of the solid char.

4.4. FTIR analysis of solid product

It was showed the spectroscopy result for effect of radiation time of solid char obtained from microwave assisted pyrolysis of kitchen waste. It was indicated the result of solid char for non-microwave absorber and with microwave absorber of activated carbon. As it was observed from 10 min to 30 min of radiation time, functional group of chemical compound in the solid char was kept remained. Only a few functional groups were removed during the microwave assisted pyrolysis reaction for both non-microwave absorbance and with microwave absorbance reaction such as O-H bond at 3680 to 3000cm^{-1} (water molecule in crystalline form), $O-NO_2$ bond at 1650 to 1600cm^{-1}, and -CO_2-(Carboxylate ions). This is due to the removal of volatile which contribute from hydrocarbon breakdown occurred during the microwave pyrolysis process. This was indicated that low radiation time only gave small effect on both non-microwave absorber and with microwave absorber of microwave assisted pyrolysis of kitchen waste. Nevertheless, when the radiation time was increased from 40 min to 60 min, it gave huge effect on the hydrocarbon compound content in the solid char. In addition, effect of additional of microwave absorber during the microwave assisted pyrolysis of kitchen waste was spotted and observed tremendously with high radiation time. Although increment of radiation time might lower the hydrocarbon content in the solid char was important to obtain for better and good for future solid fuel, high operating cost contributed from high usage of radiation time must take into consideration. As it was observed in the solid char at 50 min and 60 min, it showed low hydrocarbon content with less functional groups were spotted in the FTIR spectrum. However, it was observed that at 40 min of radiation time with additional of activated carbon as microwave absorber, low hydrocarbon content solid char was obtained with less functional group spotted in the FTIR spectrum. As compared with non-microwave absorber reaction, high amount of functional group still spotted in the FTIR spectrum and make it less possible to the solid char to be used as the solid fuel. Low hydrocarbon content in solid char was essential for the characteristic of solid fuel because the hydrocarbon might contribute to the formation of high pollutant gas during combustion.

4.5. Inorganic content of solid product

Inorganic content in the solid char was determined to analyze whether solid char obtained was safe to use as the potential solid fuel. Solid char obtained from both process without activated carbon and with additional of activated carbon exhibit low inorganic metal especially for the compound Al, Ti, Cr, Fe, Cu, Zn, Cd, Hg, and Pb. It would say that solid char derived from kitchen waste was safe to use as the solid fuel since it origin come from food waste. Results obtained were consistent with other research on the sewage sludge. [19, 20]. However, metal oxide contained in the inorganic compounds was helpful to acid gas absorption as another application after converted the solid char into activated carbon [21].

5. Conclusions

In the nutshell, microwave assisted pyrolysis process has the tendency to treat high moisture content wastes especially kitchen waste. Solid char obtained from the microwave assisted pyrolysis process contains high energy content which has the potential to become the sources of solid fuel. Instead of direct disposal of high moisture content waste such as kitchen waste in the incinerator or furnace, it is valuable and potential to implement microwave pyrolysis as an alternative for the treatment. It is not just to reduce the waste but this method is a great method to use because it also produce no contaminant by-product and produce valuable solid char.

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References

1. Tempatan, K.K.B.P.D.K. (2013). *Survey on Solid Waste Composition, Characteristics & Existing Practice of Solid Waste Recycling in Malaysia*. Final Report, Kementerian Kesejahteraan Bandar, Perumahan Dan Kerajaan Tempatan, Putrajaya.
2. Chandrappa, R.; and Das, D.B. (2012). *Waste quantities and characteristics*, in Solid Waste Management, ed: Springer.
3. Abdul Hamid, A.; Ahmad, A.; Ibrahim, M.H.; and Nik Abdul Rahman, N.N. (2012). Food waste management in Malaysia-current situation and future management options. *Journal of Industrial Research & Technology*, 2, 36-39.
4. Kalanatarifard, A.; and Yang, G.S. (2012). Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development*, 5, 11-17.
5. Wang, Q.; Ma, H.; Xu, W.; Gong, L.; Zhang, W.; and Zou, D. (2008). Ethanol production from kitchen garbage using response surface methodology. *Biochemical Engineering Journal*, 39, 604-610.
6. Knipe, A. (2005). *The management of household food waste*. Environmental Research and Consultancy. West Morden, United Kingdom.
7. Kim, M.H.; and Kim, J.W. (2010). Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global

warming and resource recovery. *Science of the Total Environment*, 408, 3998-4006.

8. Curry, N.; and Pillay, P. (2012). Biogas prediction and design of a food waste to energy system for the urban environment. *Renewable Energy*, 41, 200-209.
9. Ciplet, D. (2009). *An Industry Blowing Smoke*. Available: http://www.no-burn.org/downloads/BlowingSmokeReport
10. Wang, X.H.; Chen, H.P.; Ding, X.J.; Yang, H.P.; Zhang, S.H.; and Shen, Y.Q. (2009). Properties of gas and char from microwave pyrolysis of pine sawdust. *BioResources*, 4, 946-959.
11. Yin, C. (2012). Microwave-assisted pyrolysis of biomass for liquid biofuels production. *Bioresource Technology*, 120, 273-284.
12. Domínguez, A.; Menéndez, J.; Inguanzo, M.; and Pis, J. (2005). Investigations into the characteristics of oils produced from microwave pyrolysis of sewage sludge. *Fuel Processing Technology*, 86, 1007-1020.
13. Mujumdar, A.S.; and Menon, A.S. (1995). Drying of solids: principles, classification, and selection of dryers. *Handbook of industrial drying*, 1, 1-39.
14. Sahin, S.; and Sumnu, S.G. (2006). Physical properties of foods: Springer Science & Business Media, USA.
15. Jamaluddin, M.A.; Ismail, K.; Ghani, Z.; Ishak, M.A.M.; Idris, S.S.; Abdullah, M.F. (2011). Thermogravimetric analysis of Silantek coal, Palm Kernel Shell, Palm Kernel Shell char and their blends during combustion in Sustainable Energy & Environment (ISESEE), International Symposium & Exhibition, pp. 48-50.
16. Januri, Z.; Rahman, N.A.; Idris, S.S.; Matali, S.; Manaf, S.F.A.; Rosland, N.S. (2014). Effect of activated carbon as microwave absorbance on the yields of microwave assisted pyrolysis of palm oil mill effluent," Proceeding of 3rd International Conference on Clean Energy and Technology.
17. Januri, Z.; Rahman, N.A.; Idris, S.S.; Matali, S.; Manaf, S.F.A. (2015). Microwave assisted pyrolysis (MAP) of automotive paint sludge (APS). *Jurnal Teknologi*, 5, 7-11.
18. González, Y.S.; Costa, C.; Márquez, M.C.; and Ramos, P. (2011). Thermal and catalytic degradation of polyethylene wastes in the presence of silica gel, 5A molecular sieve and activated carbon. *Journal of Hazardous Materials*, 187, 101-112.
19. Menendez, J.; Dominguez, A.; Inguanzo, M.; and Pis, J. (2005). Microwave-induced drying, pyrolysis and gasification (MWDPG) of sewage sludge: Vitrification of the solid residue. *Journal of Analytical and Applied Pyrolysis*, 74, 406-412.
20. Agrafioti, E.; Bouras, G.; Kalderis, D.; and Diamadopoulos, E. (2013). Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis*, 101, 72-78.
21. Cui, Y.; Ji, A.M.; Liu, H.Y.; and Qian, Z.G. (295). A review on pyrolysis technology and characters of products from sewage sludge. *Applied Mechanics and Materials*, 295, 1419-1424.