Engineering Journal issn: 0125-8281

Article

Experimental Study on Utilization of Indonesian Non-Recycled Organic Waste as Renewable Solid Fuel Using Wet Torrefaction Process

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Abstract. Municipal solid waste (MSW) is a complex problem in major cities in Indonesia that has not been resolved. MSW is currently only collected and disposed to final landfill. On the other hand, national energy security is also an issue to be solved. Utilization of MSW, which is dominated by organic waste, as solid fuel can be a solution for both problems. This paper discusses an experimental study on utilization of organic waste as renewable solid fuel using a wet torrefaction process. Four types of samples were chosen to represent the four types of organic waste in MSW with the highest mass fraction found in a field survey: leaf litter, food waste, vegetable waste and fruit waste. Each sample was treated with wet torrefaction under four conditions: 150, 175, 200 and 225 ºC with holding time 30 minutes. The experimental results showed that the optimum wet torrefaction temperature for mixed organic waste is between 200 and 225 °C, which is predicted to produce a solid product with a heating value (db) of 23.22-24.44 MJ/kg, volatile matter content of 61.18-66.00%, fixed carbon content of 26.04-31.35%, ash content of 7.47-7.96%, and energy yield equal to 58%. A higher operating temperature will increase the calorific value, followed by a decrease in mass yield as a consequence of the process severity degree. However, food waste torrefaction showed different characterisics: the increase in calorific value was followed by an increase in mass yield. This is unique and different from the results of wet torrefaction on other organic wastes.

Keywords: Indonesian organic MSW, national energy security, wet torrefaction, renewable solid fuel.

ENGINEERING JOURNAL Volume 22 Issue 6
Received 16 March 2018
Accepted 20 September 2018
Published 4 December 2018
Online at http://www.engj.org/
DOI:10.4186/ej.2018.22.6.81

DOI:10.4186/ej.2018.22.6.81

1. Introduction

Fossil fuels such as petroleum, coal, and natural gas are the world's primary energy sources. About 80% of the world's energy needs depend on fossil fuels. However, this energy source is predicted to be exhausted in 40-50 years from now [1]. In addition, climate change, such as global warming is a side effect of excessive use of fossil fuels as an energy source. Emissions from fossil fuels may lead to an increase in temperatures about 1.4 - 5.8 °C in the period 1990 to 2100 [2].

Today the world is trying to reduce the increasing of carbon emissions from fossil fuels by using biomass as an alternative energy source. Currently, biomass meets 10-15% of the world's energy needs. Developed countries use biomass to meet 9-14% of their energy needs, but in developing countries nearly 20-35% of energy needs are met by biomass [3]. When biomass is burned or converted to other forms of fuel, the carbon in the biomass reacts with the oxygen in the air to form carbon dioxide, which is released into the atmosphere. If biomass is completely combusted, the amount of carbon dioxide produced will be the same as the amount taken from the atmosphere during the plant growing process. There is no net addition of CO_2 as a result of this process to the atmosphere so that biomass can be viewed as an energy source that does not produce carbon dioxide emissions [4]. A study investigated electricity which generated from organic waste in different technologies found that the cost of electricity varied from 0.097 to 0.115 $/kWh and the potential of CO_2 reduction is varied from 3.70 to 8.58 ton-CO_2 per MWh electricity production from organic waste in palm oil plant, landfill gas, cassava plant, and in swine farm [5].

Indonesia not only faces weak energy security, it also faces the complicated problem of anticipating a growing amount of municipal solid waste (MSW), especially in big cities such as Jakarta, Bandung, Semarang and Surabaya. The Ministry of the Environment has reported that in 2008 Indonesia produced 38.5 million tons of waste, which is expected to increase by 2-4% per year. Waste management systems in Indonesia generally only consist of collecting and transporting MSW to temporary landfills (TPS) and final landfills (68.64%). The rest is stored in soil (9.47%), composted (7.10%), burned (4.73%), dumped into rivers (3.55%), and others (6,51)[6].

MSW is categorized into organic waste, food waste, paper waste, recycled plastic waste, non recycled plastic waste, rubber, and textiles [7]. Organic waste consists of leaves, vegetables and wood. The mass fraction of Bandung's garbage, obtained through a survey in a number of temporary disposal places (TPS), is as follows: organic waste 35.58%, food waste 22.58%, paper 13.67%, recyclable plastic 7.06%, non-recycled plastic 5.69%, glass 3.19%, metal 3.31%, textile 1.94%, rubber 0.68%, styrofoam 0.25%, electronic waste 0.56%, and other wastes 5.49%. Approximately 25% of waste consists of paper, glass, recyclable plastic and cans/metal, which are usually taken by scavengers because they still have economic value. The remaining 75%, consisting of organic waste, food scraps, non-recycled plastic, textiles, rubber, and others, is waste that will be transported to landfills but still has the potential to be used as solid fuel.

The characteristics of municipal waste in other major cities in Indonesia are not much different from the characteristics of MSW in Bandung. A comparison of the composition of MSW in the major cities in Indonesia (Semarang, Surabaya, Jakarta and Bandung) is shown in Table 1 [8]. The data show that the composition of waste is almost the same in these big cities and is dominated by organic waste with an average of about 66% and plastic averaging at about 10%. These results are not much different from the composition of waste research results conducted by the Ministry of Environment, which showed that the components of kitchen waste or organic waste is the largest component, with a fraction of 58% [6].

Table 1. MSW composition for some big cities in Indonesia [8].

No	Type of Waste	Composition (%)				Average (%)
		Semarang	Surabaya	Jakarta	Bandung	
1	Organic	61.95	71.85	68.12	63.52	66.36
2	Plastic	13.39	12.45	11.08	4.90	10.46
3	Paper	12.36	7.60	10.11	10.42	10.12
4	Textile	1.55	0.90	2.45	1.70	1.65
5	Rubber	0.50	0.90	0.55	4.90	1.71
6	Metal	1.80	0.54	1.90	0.95	1.30
7	Glass	1.72	1.94	1.63	1.45	1.69
8	Other	6.83	3.82	4.12	12.16	6.73

Bandung is one of the big cities in Indonesia. Bandung City and its surroundings produce about 1500 tons of MSW every day. The amount dumped in final landfills every day as non-recycled municipal waste is about 1124.04 ton. Organic waste is the largest waste component contained in MSW that is landfilled, with a mass fraction of 50.86%. This is followed by plastic waste at 25.79%, consisting of 11.74% recyclable plastic waste, dominated by HDPE plastics waste, 13.72% non-recycled plastic waste dominated by colored plastic packaging (10.09%), and laminated aluminum plastic (1.98%) [9]. As stated before, organic wastes are the largest component of MSW, at about 50.86%. This result is similar to that of studies conducted by previous researchers: 68% [6], 56.2% [7], and 66% [8]. However, the percentage of organic waste was relatively smaller compared to previous researches; this is because of the location of our field survey, which was conducted at a final landfill (TPA), where some of the organic waste has started to decompose. The previous researches were done at temporary landfills (TPS), where the condition of organic waste is fresher. Further field survey has showed that Indonesian non-recycled MSW consists of leaf litter (34.67%), food waste (23.33%), vegetable waste (14.33%), fruit waste (11.00%), and non-recycled plastic (16.67%) [9].

A preliminary study on utilization of Indonesian non-recycled MSW has already been done by investigating proximate and calorific values, providing data on water content, physical properties, and calorific value for each waste component, as shown in Table 2 [9]. In addition, there are also some calculations to predict organic and mixed characteristics of a solid fuel from MSW. The water content of organic waste is very high, i.e. 61.32%. Even when plastic waste is included, the water content is still so high (51.38%) that it needs drying before it can be used as fuel. If pre-treatment is carried out only by surface-water drying, the calorific value of the organic waste mixture is 16.74 MJ/kg, much lower than Indonesian coal at 23.24 MJ/kg and sub-bituminous coal at 19.33-22.1 MJ/kg.

Solid fuels produced from raw non-recycled organic MSW are rich in volatile matter content (76.97%) and have low fixed carbon content (15.94%), so they cannot be used directly to substitute coal because of its different combustion characteristics. Some efforts that can be done to improve it characteristics are modification of the combustion system, blending for co-firing with certain composition, or pre-treatment to improve the fixed carbon content by carbonization or torrefaction.

Table 2. Physical properties and calorific value (HHV) of raw organic waste [9].

No	Non Recycled MSW Components	Mass Fraction (%)	Physical Properties (%) – dry based			Moisture (%)		Calorific Value (MJ/kg)		
			VM	FC	ash	inherent moisture	total moisture	dry-based	air-dried	as received
1	Leaf litter	34.67	73.17	17.87	8.96	12.32	40.67	19.62	17.20	11.64
2	Food waste	23.33	84.24	15.11	0.64	8.51	65.00	18.00	16.47	6.30
3	Vegetable waste	14.33	77.09	13.68	9.22	11.46	88.25	18.25	16.16	2.14
4	Fruit waste	11.00	73.38	14.59	12.03	9.92	83.53	18.38	16.56	3.03
5	Non Recycled Plastic	16.67	99.30	0.04	0.66	0.39	1.68	45.80	45.62	45.03
6	Mixed organic MSW	83.33	76.97	15.94	7.08	10.79	61.32	18.77	16.74	7.26
7	Non Recycled MSW	100.00	80.69	13.29	6.01	9.06	51.38	23.27	21.17	11.31
8	Indonesian coal [a)]	–	47.13	46.40	6.47	16.31	34.40	27.14	23.24	17.46
9	Sub-bituminous coal	–						19.33-22.1 (dry basis)		

[a)] Samples were taken from coal yard in Indonesian power plant.

The moisture content of raw organic waste from municipal solid waste in Indonesia is high, so it needs pre-treatment to reduce its water content before it can be used as solid fuel [7]. Wet torrefaction technology is suitable for biomass types that have high water content, including municipal solid waste (MSW), as this process does not require initial drying such as dry torrefaction [10]. Wet torrefaction is an alternative pretreatment to produce solid fuel from municipal solid waste (MSW) using high pressure and high-temperature water as medium. Wet torrefaction of Japanese MSW samples produced calorific values similar to that of sub-bituminous coal, decreased chlorine content and the product is recommended for use as a mixture in co-firing at 20% [11].

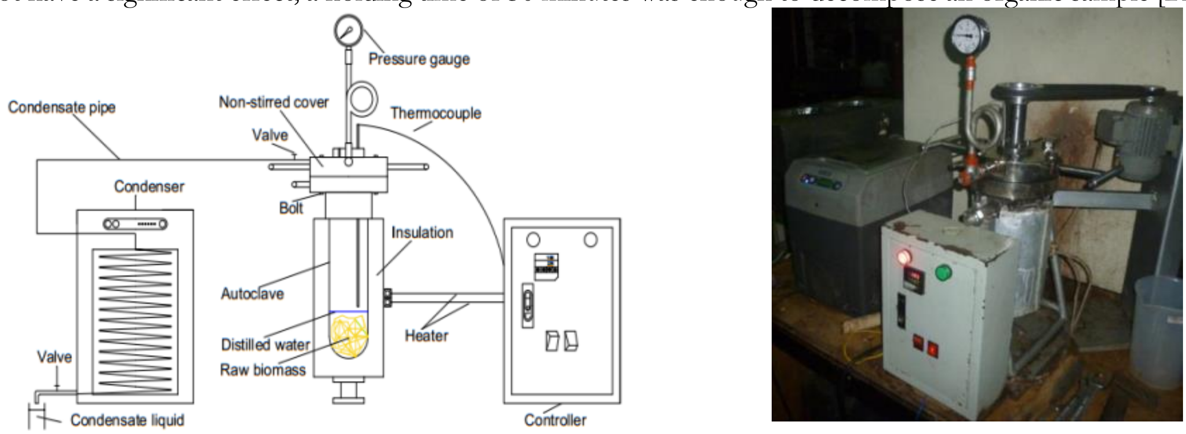
Previous related researches [12–16] have proved that the process of wet torrefaction can produce a uniform pulp product with 75% reduction of waste volume and convert it to a solid product with carbon content mostly in solid (char), about 49-75%, in liquid form about 20-37%, while the carbon content in the gas phase was only 2-11 %. The wet torrefaction process also increases the energy density of the solid product with a calorific value almost equal to sub-bituminous coal. Other researches have investigated the reduction of chlorine content in MSW through the process of wet torrefaction [17–20]. The results showed that wet torrefaction can significantly reduce the chlorine content in the solid product until it is safe to be used as fuel.

Our literature review showed that if organic waste contained in Indonesian non-recycled MSW is used as solid fuel without pretreatment, then the characteristics of the product will be much different from the characteristics of Indonesian coal, especially in terms of calorific value and volatile matter content. Therefore, it cannot to be blended or co-fired without modifying the combustion chamber. In this study, some experiments were conducted to determine the effect of wet torrefaction for improving the fuel properties of Indonesian non-recycled MSW, especially organic waste, so that its fuel properties can be more similar to those of Indonesian coal.

2. Material and Experiment

The objective of this study is to obtain data about the effect of wet torrefaction process on increasing the fuel properties of organic MSW and find the optimum temperature that can produce renewable solid products with a calorific value equivalent to sub-bituminous coal of 19.33-22.1 MJ/kg.

Wet torrefaction is a thermal decomposition process that uses high temperature and pressurized liquid to decompose biomass or MSW in order to increase its fuel properties. A wet torrefaction reactor is a pressure vessel designed to operate at high temperatures and high pressures. The reactor used in this experiment was a laboratory scale reactor with a volume of 2.5 liters and with schematic and installation as shown in Fig. 1. The main parameters of the wet torrefaction process are temperature, residence time, and solid load. Previous research using a laboratory scale reactor with 2.5 liter volume showed that the holding time parameter did not have a significant effect; a holding time of 30 minutes was enough to decompose an organic sample [21].



(a) (b)

Fig. 1. Schematic (a) and installation (b) of lab scale reactor.

The feedstock materials studied are the most prevalent organic waste components according to the result of a previous field survey for Indonesian MSW: leaf litter (41.50%), food waste (27.97%), vegetable waste (17.32%) and fruit waste (13.21%) [9]. Mahoney leaves were used as representative of leaf litter. Rice was used as representative of most food waste in Indonesia. Cassava leave stalks were chosen as vegetable waste sample based on the most prevalent vegetable waste found in the survey. Banana peel was used as representative of fruit waste.

Most of the samples are lignocellulosic biomass. Temperatures higher than 150 ºC are necessary to break amorphous cellulose oligomers to their monomer components. Crystalline cellulose portions are much less reactive under HTC conditions, due to their strong intra and intermolecular hydrogen bonds, so that temperatures above 180 ºC are required to begin decomposition to glucose monomer. Apparently, temperatures of less than 230 ºC and relatively short reaction times are required to hydrolyze hemicellulose using HTC. Lignin appears to be relatively unreactive under HTC conditions. When hydrothermal pretreatment is performed on lignin, reaction temperatures higher than typical HTC conditions (180–300 ºC) are frequently used [22].

In this research, the experiments were more focused on investigating the effect of temperature on the characteristics of solid products for each organic waste sample. The selected temperature variations are 150, 175, 200, and 225 ºC by considering the degradation temperature of cellulose and hemicellulose. Temperatures above 225 ºC are not carried out considering the difficulties for implementation because it requires very high pressure reactor and equipment. The solid load is the ratio between the mass of the sample and the mass of the water. This was kept constant at 1:2.5. Holding time is 30 minutes. A stirrer was used at 675 rpm. The experimental parameters and sample identities (ID) are listed in Table 3.

The experiment was done to investigate the effect of the wet torrefaction process on improving the fuel properties of waste by analyzing the solid mass yield, proximate, ultimate and calorific values. The solid mass yield is obtained by filtering the solid product using a mesh size sieve 120. Data about calorific value, physical and chemical properties were obtained for comparison with the characteristics of Indonesian coal.

Tabel 3. Experimental parameters and sample ID.

Sample	Temperature	Holding Time	Sample ID
Leaf litter	Raw 150 °C 175 °C 200 °C 225 °C	30 minutes	00000-TW 15030-TW 17530-TW 20030-TW 22530-TW
Food waste (rice)	Raw 150 °C 175 °C 200 °C 225 °C	30 minutes	00000-FdW 15030-FdW 17530-FdW 20030-FdW 22530-FdW
Vegetable waste (cassava leave stalks)	Raw 150 °C 175 °C 200 °C 225 °C	30 minutes	00000-VW 15030-VW 17530-VW 20030-VW 22530-VW
Fruit waste (banana peel)	Raw 150 °C 175 °C 200 °C 225 °C	30 minutes	00000-FW 15030-FW 17530-FW 20030-FW 22530-FW

3. Results and Discussion

In this section, the experimental data on physical appearance, physical properties, chemical composition, and calorific value are presented.

3.1. Effect of Wet Torrefaction on Physical Properties of Leaf litter

The color of the solid product generally changed according to temperature. The higher the temperature, the darker the color, as shown in Fig. 2 and Fig.3.

Fig 2. Wet product of leaf litter, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

At temperatures of 150 °C and 175 °C, leaves and large-size twigs are still visible, which indicates that the leaf litter and twigs have not decomposed significantly. At a temperature of 200 °C there was a change, where

DOI:10.4186/ej.2018.22.6.81

the physical form of leaves and large-size twigs is no longer visible, the sample has been reduced in volume and has a darker color. Samples at a temperature of 225 °C have a significantly different physical form, where the structure of leaves and twigs is almost no longer visible; the product is already in the form of small grains and partially in powder form, which indicates that the leaves and twigs have been decomposed. The smell of the solid product is quite like the smell of roasted coffee.

Fig 3. Dried product of leaf litter, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Higher operating temperatures have a tendency to produce a solid product with lower volatile matter (VM) content, higher fixed carbon content (FC), less inherent moisture (IM), higher calorific values, but result in greater ash content and smaller mass yields, as shown in Table 4.

Table 4. Physical composition and calorific value of leaf litter products.

No	Sample ID	Mass Yield (%)	Physical Properties (%)			Moisture Content (%)		Calorific Value (MJ/kg)		
			VM	FC	Ash	IM	TM	db	adb	ar
1	00000-TW	100.0	73.00	18.10	8.90	12.32	40.67	19.78	17.34	11.73
2	15030-TW	82.9	68.68	19.29	12.03	9.74	77.58	19.86	17.92	4.45
3	17530-TW	82.3	65.62	21.42	12.96	9.38	76.42	20.01	18.13	4.72
4	20030-TW	73.9	63.19	23.50	13.31	7.53	76.11	20.97	19.39	5.01
5	22530-TW	66.9	61.42	25.03	13.55	6.45	74.16	21.36	19.99	5.52

3.2. Effect of Wet Torrefaction on Physical Properties of Vegetable Waste

The physical appearance of the feedstock and the products are shown in wet condition in Fig. 4 and in dried condition in Fig. 5. At temperatures of 150 °C and 175 °C, the cassava leave stalks were still large in size. When the reactor was opened there were some samples stuck in the stirrer that could not be broken by hand, only by using scissors. This shows that in these conditions the fibers in the vegetable waste remained largely unraveled. The space inside the rods looked empty, indicating that some of the components inside the stalk had dissolved in the water. At a temperature of 200 °C there was a change in physical shape, making the sample darker in color and smaller in size. A small amount of sample was wrapped around the stirrer and could easily be broken by hand. This shows that in this condition most of the vegetable waste components had begun to decompose. The sample at 225 °C had a significant shift in physical form where the cassava stem structure was almost no longer visible and had turned into small grains and a larger amount into powder. The smell of the solid product was quite stinging. This indicates that the sample had been unraveled.

Higher operating temperatures have a tendency to produce solid products with lower VM content, higher FC content, less inherent moisture, higher calorific values, slightly decreased ash content and significantly lower yield mass, as shown in Table 5.

Fig 4. Wet product of vegetable waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Fig 5. Dried product of vegetable waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Table 5. Physical composition and calorific value of vegetable waste products.

No	Sample ID	Mass Yield (%)	Physical Properties (%)			Moisture Content (%)		Calorific Value (MJ/kg)		
			VM	FC	Ash	IM	TM	db	adb	ar
1	00000-VW	100.0	77.16	13.48	9.36	12.01	91.06	17.70	15.58	1.58
2	15030-VW	73.5	79.57	12.44	7.98	7.68	92.76	18.19	16.80	1.32
3	17530-VW	61.7	78.91	14.56	6.53	5.90	90.20	21.05	19.81	2.06
4	20030-VW	55.0	75.74	18.00	6.26	5.48	90.28	22.84	21.59	2.22
5	22530-VW	37.1	72.16	21.43	6.40	4.68	84.21	23.48	22.38	3.71

3.3. Effect of Wet Torrefaction on Physical Properties of Food Waste

At temperatures of 150 °C and 175 °C solids with similar characteristics were produced, i.e. agglomerated and dry. Although it had almost the same characteristics as the solid product at 150 °C, the solid product at 175 °C had a darker color and less mass yield. The solid product from food waste resulted at a temperature of 200 °C and 225 °C was in the form of a black powder with a very strong odor. This is quite different from the conditions of the solids produced at lower temperatures. When compared to a temperature of 200 °C, at 225 °C a more solid mass yield with a darker color was produced. The physical appearance of the feedstock and the products in wet condition are shown in Fig. 6 and in dried condition in Fig. 7.

Fig 6. Wet product of food waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Fig 7. Dried product of food waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Higher operating temperatures have a tendency to produce solid products with lower VM content, higher FC content, less inherent moisture, and higher calorific values. A significant increase of FC was found in products at temperatures of 200 °C and 225 °C. The ash content of all products was quite small, i.e. about 0.18-1.16%. There was an anomaly in the resulting mass yield being smaller at temperatures below 175 °C while rising at higher temperature, as shown in Table 6.

Table 6. Physical composition and calorific value of food waste products.

No	Sample ID	Mass Yield (%)	Physical Properties (%)			Moisture Content (%)		Calorific Value (MJ/kg)		
			VM	FC	Ash	IM	TM	db	adb	ar
1	00000-FdW	100.0	84.41	15.02	0.57	8.63	57.67	17.92	16.37	7.58
2	15030-FdW	18.1	79.88	18.96	1.16	7.00	83.97	19.93	18.54	3.20
3	17530-FdW	6.3	80.31	18.90	0.79	5.00	81.17	21.64	20.56	4.07
4	20030-FdW	15.5	62.90	36.74	0.36	4.00	76.47	25.90	24.86	6.09
5	22530-FdW	34.1	50.64	49.18	0.18	3.82	71.89	27.72	26.67	7.79

3.4. Effect of Wet Torrefaction on Physical Properties of Fruit Waste

At temperatures of 150 °C, 175 °C and 200 °C solids were produced with similar characteristics, i.e. agglomerated and dry. The solids at higher temperatures had a darker color. Banana aroma could be smelled in the solid products that were produced at temperatures of 150 °C and 175 °C. The solid product of wet fruit waste at 225 °C was blackish brown, had no agglomeration and was mostly powder or small lumps that could be easily crushed by hand. The physical appearance of the feedstock and products in wet condition are shown in Fig. 8 and in dried condition in Fig. 9.

Fig 8. Wet product of fruit waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Fig 9. Dried product of fruit waste, from left to right: raw, 150 °C, 175 °C, 200 °C and 225 °C.

Table 7. Physical composition and calorific value of fruit waste products.

No	Sample ID	Mass Yield (%)	Physical Properties (%)			Moisture Content (%)		Calorific Value (MJ/kg)		
			VM	FC	Ash	IM	TM	db	adb	ar
1	00000-FW	100.0	73.50	14.70	11.80	9.92	91.26	18.21	16.40	1.59
2	15030-FW	41.2	73.89	13.70	12.41	7.15	93.84	20.27	18.82	1.25
3	17530-FW	40.5	71.23	15.66	13.11	7.13	93.23	21.10	19.59	1.43
4	20030-FW	32.9	68.65	21.89	9.46	4.00	92.87	25.14	24.13	1.79
5	22530-FW	21.1	68.33	26.47	5.20	2.68	87.02	28.40	27.64	3.69

Higher operating temperatures have a tendency to produce solid products with lower VM content, higher FC content, less inherent moisture, higher calorific values, decreased ash content, and significantly reduced mass yield, as shown in Table 7.

3.5. Discussion

Based on the experimental data that were obtained on each organic waste and assuming that during the wet torrefaction process there is no interaction between the waste components, some calculations to predict the characteristics of the mixed solid waste product were done by considering the composition of each waste component according to the field survey results: leaf litter (41.50%), food waste (27.97%), vegetable waste (17.32%) and fruit waste (13.21%). The calculation results are shown in Table 8. Equations 1 and 2 are used to calculate the mass yield and energy yield.

$$Mass\ Yield\ (\%) = \frac{Product\ Mass\ (db)}{Raw\ Feed\ stock\ Mass\ (db)}\ x\ 100\% \quad (1)$$

$$Energy\ Yield\ (\%) = \frac{Product\ Energy\ Content\ (db)}{Raw\ Feed\ stock\ Energy\ Content\ (db)}\ x\ 100\% \quad (2)$$

Table 8. Calculation of physical composition and calorific value of mixed organic waste products.

No	MSW Components	Mass Yied (%)	Physical Properties (%)			Moisture (%)		Calorific Value (MJ/kg)			Energy Yield (%)
			VM	FC	Ash	IM	TM	db	adb	ar	
1	00000-Mix	100.00	76.97	15.99	7.04	10.92	60.83	18.69	16.64	7.48	100.00%
2	15030-Mix	57.62	74.39	17.27	8.34	8.27	84.14	19.65	18.02	3.13	60.23%
3	17530-Mix	51.94	72.77	18.77	8.46	7.25	82.36	20.79	19.29	3.64	56.66%
4	20030-Mix	48.88	66.00	26.04	7.96	5.72	80.88	23.22	21.93	4.40	57.91%
5	22530-Mix	46.49	61.18	31.35	7.47	4.91	76.97	24.44	23.28	5.60	58.16%

The increase in temperature reduces the inherent moisture content due to the dehydration process, which decomposes inherent or bonded water in organic waste into surface moisture. With the application of heat, hydronium acid ions ($H3O^+$) and hydroxyl base ions (OH^-) are formed through decomposition. The properties and structure of each substance change significantly at its critical point, indicating hydrogen bonds breaking up and separating the chain structure of the group [10].

Hemicellulose hydrolysis occurs at about 180 °C, but the detailed reaction is not known for certain. Cellulose undergoes hydrolysis in wet torrefaction of 200 °C. Lignin is hydrothermally degraded above 200 °C due to the large number of ether bonds [23]. Leaf litter is ligno-cellulose waste and in our experiment decomposed significantly at 200 °C and 225 °C, indicated by the significant mass reduction and increase of the calorific value, as shown in Table 4. Significant mass reduction of vegetable and fruit waste started at lower temperature. An anomaly was found in the mass yield of food waste (starch based waste) as shown by Fig. 10. The mass yield reduced normally until 175 °C but increased at temperature higher than 175 °C.

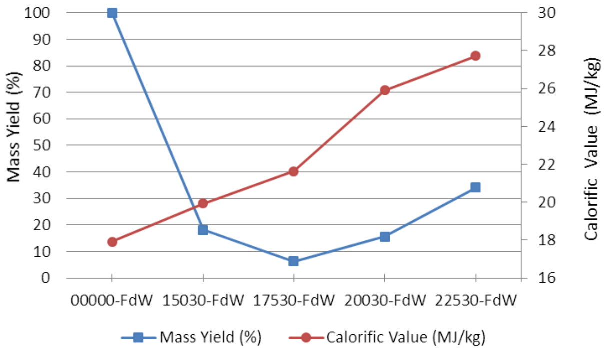


Fig 10. Effect of temperature on mass yield and calorific value of food waste.

The experimental results showed generally that a higher operating temperature of the wet torrefaction process will increase the calorific value, accompanied by a decrease in yield mass as a consequence of the severity of the process. However, an anomaly found in the result of the food waste experiment was an increase of the calorific value accompanied by an increased mass yield. This is unique and different from the general results of wet torrefaction of the other organic wastes.

Higher wet torrefaction temperatures also decrease the VM content and increase the FC content, as shown in Fig. 11 (left). This occurs because during the process of wet torrefaction, decarboxylation and decarbonylation reactions take place [23]. The process of wet torrefaction at higher temperatures results in products that have chemical properties that are increasingly close to the characteristics of coal, as shown by Fig. 11 (right).

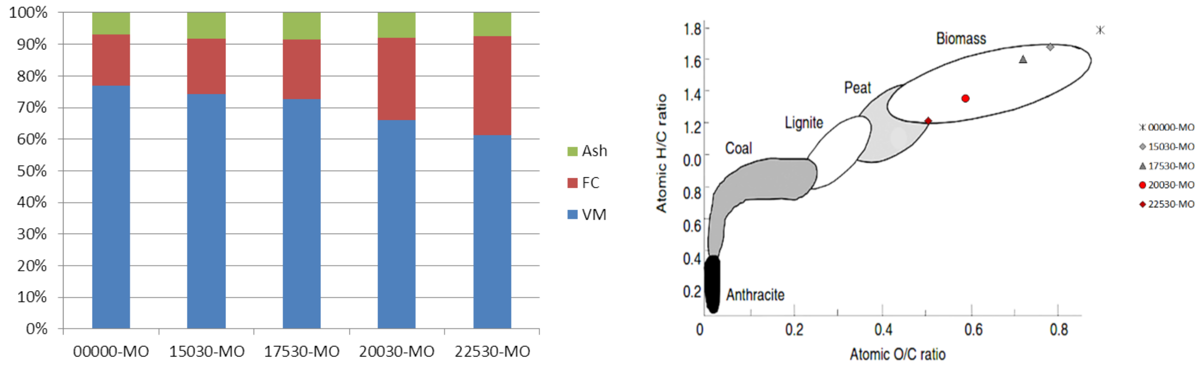


Fig. 11. Physical properties (left) and chemical properties (right) of raw and products from mixed organic waste.

The lowest energy yield was produced at a temperature of 175 °C, which was slightly increased at higher temperature, as shown in Fig. 12 (left). This is due to the contribution of food waste, which increased at temperatures more than 175 °C. The effect of temperature on mass yield and the heating value of the mixed organic solid waste is shown in Fig. 12 (right). Based on the shape of the two curves, considering only the increase of the calorific value and the decrease of the mass yield as indicators of reaction severity, it can be predicted that the optimum temperature is between 200 °C and 225 °C, because in that region the mass yield gradient is constant and the calorific value gradient starts to decline.

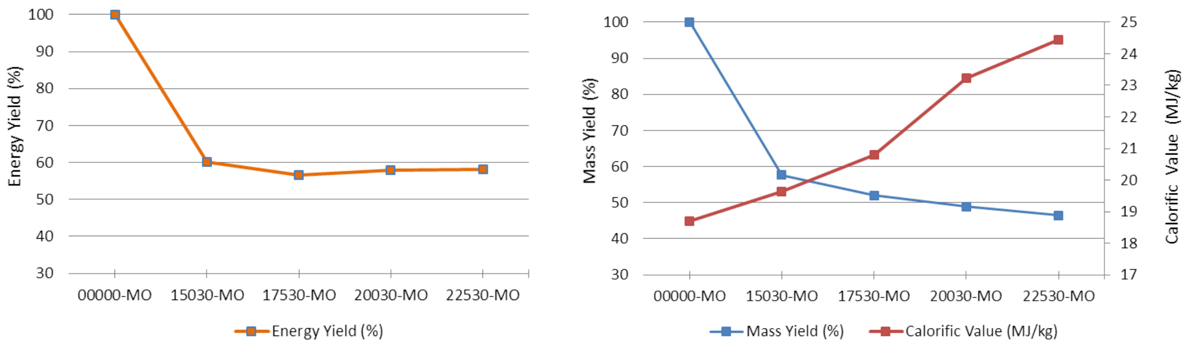


Fig 12. Effect of temperature on energy yield of mixed organic waste (left) and comparison between mass yield and calorific value of raw and products from mixed organic waste (right).

4. Conclusion

Lower temperature limit produced higher energy yields but the calorific value of the product is lower than coal. Higher temperature limit produced solid product with higher calorific values than coal but lower energy yields due to excessive torrefaction resulting in low mass yields. Based on the characteristics of each waste component, assuming there is no interaction between the waste components during the torrefaction process and considering only the increase of the calorific value and the decrease of the mass yield as indicators of reaction severity, it can be predicted that the optimum wet torrefaction temperature for organic waste in relation to the composition of MSW from the result of the field survey lies between 200 and 225 °C, which is predicted to produce a solid product with an HHV_{db} heating value of 23.22-24.44 MJ/kg that higher than sub-bituminous coal, VM content of 61.18-66.00%, FC content of 26.04-31.35%, ash content of 7.47-7.96% with energy yield about 58%.

Based on the experimental data and the analysis it can be concluded that the wet torrefaction process was generally effective in reducing the inherent moisture content and increasing the calorific value. The process of wet torrefaction was also effective in reducing the ash content, especially in the vegetable waste and fruit waste samples, except in the leaf litter sample, where the ash content actually increased. In general, the experimental result shows that a higher operating temperature of the wet torrefaction process will increase the calorific value accompanied by a decrease in yield mass as a consequence of the severity of the process. However, an anomaly was found in the result of the food waste experiment, i.e. an increase of the calorific value accompanied by an increased mass yield. This is unique and quite different from the characteristics of the other waste samples, which are lignocellulosic waste. Further research or testing is needed to understand the mechanism that occurs in the wet torrefaction process for food waste which is starch-based waste.

The main obstacle in the utilization of municipal solid waste in Indonesia and other developing countries as solid fuel is the condition of organic waste and plastic waste that is mixed and difficult to separate, so it is necessary to conduct further experiments to determine the effect of wet torrefaction processes on mixed organic and plastic waste including investigation of interaction between components of waste during the process. In addition, it is also necessary to try to make briquettes from solid products produced to increase the density and requirements in storage and transport.

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