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Solid fuel processing of refuse derived fuel (RDF) from agricultural waste with latex rubber binder

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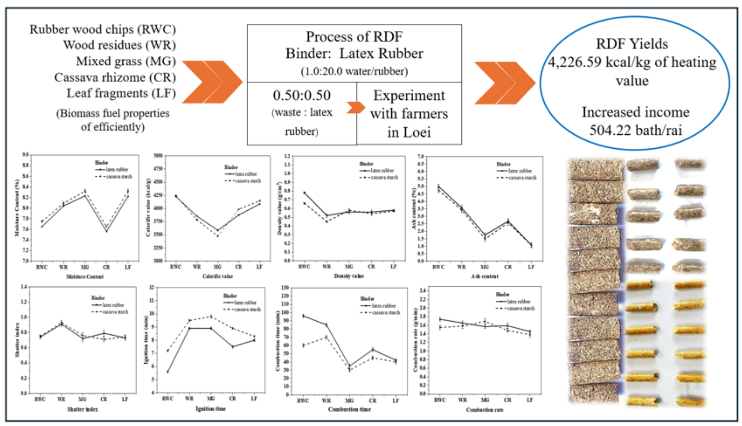
Abstract

This research aims to experiment with the conversion of solid fuel from waste (RDF) with latex rubber binder. Agricultural waste, which is currently biomass fuel, significantly impacts global warming. If such waste can be converted into RDF, it could be an alternative to reduce greenhouse gas emissions. There are 5 types of waste materials making up RDF: rubber wood chips (RWC), wood residues (WR), mixed grass (MG), cassava rhizome (CR), leaf fragments (LF). The analysis of biomass fuel properties of these materials can be used to transform the materials into biomass fuel efficiently. The heating values range from 14,693 to 17,065 kJ/kg. The energy values range from 3,509.36 to 4,075.91 kcal/kg. The moistures range from 10.35 to 16.80 % by weight. The densities range from 310 to 550 kg/m^3. The results of the RDF processing test using latex rubber as a binder at the ratio of 0.50:0.05 obtained better results than cassava starch sludge. The results showed that the energy values range 3,474.50-4,245.65 kcal/kg., moistures range 7.56-8.32 by wt., densities range 0.45-0.78 g/cm^3, ash contents range 1.06-5.00 by wt., shatter indexes range 0.71-0.93, ignition times range 5.6-9.8 min., combustion times range 30-96 min., combustion rates range 1.38-1.74 g/min. The RDF with a 1.0:20.0 water-to-rubber ratio yields the best efficiency, with 7.68% moisture content and 5.00% ash content. The ratio of water to fresh rubber of 1.0:20.0 makes RFD the most effective (4,226.59 kcal/kg of heating value, 7.68% moisture content, 5.00% ash content). The cost and profit analysis of making RDF showed that processing RDF from cassava rhizomes (CR) can provide the highest profit at 504.22 baht/rai. The results from this research can help many farmers in Loei Province to increase their incomes.



Keyword: Refuse Derived Fuel (RDF); Agricultural Waste; Latex Rubber

1. Introduction

Waste increased by no less than 0.69 percent in line with the growth of the world's population by 1.00%, resulting in greenhouse gases accumulating in the world [1,2] such as methane and carbon dioxide [3,4]. Especially the impact of the world's increased energy consumption activities from fuel oil and coal. Therefore, approaches to convert waste into refuse-derived fuel (RDF) were very interesting [2,5]. RDF can be produced from solid waste and mixtures of agricultural wastes such as wood chips, leaves, grass, wheat straw, Sawdust of rubber wood, rubber seeds, coconut shells, cassava rhizomes, bagasse, corn cobs, rice straw, and rubber wood chips that were mixed with dry cassava starch sediment [6,7,8,9]. RDF from plastics and paper is the main fraction in RDF (50–80%), while the remaining fractions include organic matter, wood and textiles [10]. RDF produced from agricultural waste can provide an average of more than 19.91-25.00 MJ/kg of heat energy [8].

Thailand currently uses renewable energy extensively and relies heavily on natural gas. Both government and private sectors value and support alternative energy. Biomass is one of the significant alternative and renewable energy sources. Using biomass can reduce carbon dioxide in the atmosphere. This can help carbon balancing. Thailand is an agricultural country and has a variety of biomass. They can be obtained from agricultural wastes in the field. In Thailand, there is approximately 134 million tons of waste material a year. Only 72 million tons were put to use, while the rest 62 million tons or 46% were unused, comparable to 562,223.8 TJ or 13,348 ktoe of energy [2,5].

When the harvest season arrives, there are a lot of agricultural leftover materials remaining left unused in the field. If farmers handle them improperly, such as burning in open areas, it brings negative impact on the environment. This includes the release of carbon dioxide, smoke, ash and small dust particles (PM2.5) that are harmful to human health. In addition, it can cause soil quality to deteriorate and have long-term impact on the environment. Loei Province has at least 4 factories. Their fuel costs for production are high. In the case of Sri Trang Company, the fuel costs of drying rubber with biofuels like wood chips (chopped wood), are 1,000 tons/month, worth 1.210 million baht/month or approximately 14.520 million baht/year. Most of the wood ships are obtained from the private sector in the northeastern and northern regions. With the fuel costs this high, the industrial sector needs to seek for biofuels with higher efficiency as an alternative to reduce production costs. Besides the rubber farming sector needs additional income from rubber plantations. The use of agricultural waste materials to produce energy still has many limitations, due to variety of plant species energy properties, The uneven nature of biomass, and the variety of material properties due to seasonal differences[11]. Agricultural biomass waste materials in Loei province include rubber wood chips, wood residues, mixed grass, cassava rhizome, leaf fragments. They can be mixed and compressed into compressed solid fuel or RDF, with high efficiency [2,5,6,7,8,9]. Furthermore, it can also solve the problem of agricultural fuel combustion and reduce the problem of greenhouse gas emissions. It is highly probable to increase the farmer's income by selling biomass fuel to rubber processing factories in Loei Province, such as Sri Trang Industry Company (Khao Loei Branch), Charoen Company, Rubber Commodities (Loei Branch). These factories has a demand of biomass fuel to use in the rubber production process. Therefore, this research was conceived to experiment with using agricultural waste materials to transform them into solid waste-derived fuel (RDF), with latex as the main binder.

2. Materials and methods

Preparation of fuel samples and binders

Collect agricultural waste materials including rubber wood chips (RWC), wood residues (WR), mixed grass (MG), cassava rhizome (CR), leaf fragments (LF) and prepare them for making RDF fuel, as shown in Figure 1. Then finely grind them with a 5.0 mm. resolution hammer grinder, and dry weigh the materials. The binder is the latex cassava starch from an industrial factory in the province. Prepare a sample of latex rubber and water at the ratio of 1.0:20.0. The latex rubber is in white liquid form, with the density of approximately 0.975-0.980 g/mL, the pH of approximately 6.5 - 7.0, the viscosity of 12-15 centipoises. The tapioca starch has a pH of 4.12, TS 126.31 g/L, VS 125.32 g/L, COD 24 g/L, TOC 2.55 g/L, TNK 0.92 g/L and C/N ratio 2.77. Afterwards, Experiments were performed with RDF mixtures between agricultural waste materials and binders with ratios of 0.50:0.50, 0.50:1.00, 0.50:1.50, 0.50:2.00, 0.50:2.50 and 0.50:3.00 by weight. Then, the mixed materials were compressed into RDF pellet forming using an RDF press machine. The resulting RDF is then dried at room temperature before being analyzed for energy values in the laboratory.

Fig. 1 Preparation of RDF.

Heating value

Heat analysis of compressed fuel from agricultural waste materials was performed according to ASTM D5865 with thermal energy analyzer (Bomb Calorimeter). Bring samples of compressed fuel from agricultural waste materials to compress and weigh. Put them in a sample cup and hold the coil wire into shape, by allowing the wire to touch the sample only. Then put them into the bomb and compress the oxygen gas with 30 atmospheres pressure. After that, place them in a bomb tank and add 2 liters of distilled water to the tank, proceed to the ignition with the bomb, and record the results [13].

Moisture content

Moisture content of compressed fuel from agricultural waste materials was analyzed according to ASTM D 317. The moisture content was determined by pulverizing 1g of the dried sample of the briquettes into a crucible and placed inside an electric oven set at 105°C for 30 min. Then weigh it (W_1) and put it in an oven at 105 degrees Celsius for about 1 hour. Leave it to cool at room temperature in a desiccant jar for 15 minutes and then weigh it (W_2). Then calculate the moisture content using equation (1) [14].

$$\text{Moisture content} = (W_1-W_2)/W_1 \times 100 \quad (1)$$

Where, W_1= weight of the sample before drying, (gram); W_2= weight of the bone dried sample, (gram)

Density value test

The relative density of samples was calculated by measuring the volume and weight. It was calculated in accordance using equation (2) [15].

$$D = M/V \quad (2)$$

Where, D is the density of the fuel briquette (g/cm^3)., M is the mass of the fuel pellet (g) and V is the volume of the fuel pellet (cm^3).

Ash Content

The ash content was determined by pulverizing 1 g of dried sample of the briquettes into a crucible and heating without lid in a “GALLENKAMP S2-0G110” muffle furnace at 750C for 90 minutes. The crucible was taken out and placed in a desiccator for cooling. The sample was then weighed. The procedure was repeated until a constant weight was attained. Based on ASTMD-3174, the residue was reported as the ash content on a percentage basis. The procedure was repeated for all the samples and the ash content was calculated using equation (3) [16].

$$\text{Ash content, } (\%) = \frac{w_3-w_4}{w_2-w_1} x100 \quad (3)$$

Where, W_1 = weight of the crucible (g), W_2 = weight of crucible with the sample before oven drying (g), W_3 = weight of crucible with the sample after oven drying (g), W_4 = weight of crucible with the sample after heating in a muffle furnace (g).

Drop Shatter Test

Put the fuel briquettes from agricultural waste into plastic bags. Release them from the height of 2.00 meters onto the concrete floor. Then the remaining fuel briquettes were weighed and the crack index was calculated using equation (4) [17].

$$R = W/W_f \quad (4)$$

Where, R= Drop Shatter, W= weight before testing (kg) and W_f = weight after testing (kg).

Ignition Time

The ignition time was determined by igniting the briquettes on a Bunsen burner by setting the edges of the briquettes under a steady flame from the burner. The time it takes for each sample to ignite and sustain combustion was recorded with the aid of a stopwatch.

Testing material

Ignition, the introduction of compressed fuel from each agricultural waste material, well-molded ratio to burn and process the timer. Then compare the ignition time in the experiment kit by bringing the compressed fuel from 200 grams of agricultural waste to boil 1 liter of water in the radiator, and record the duration from when the compressed fuel starts to ignite until the power goes out. Record the time of ignition, and the burning time and calculate the fuel combustion rate.

Analysis of heavy metals in ashes.

Analysis of heavy metals in ashes by the accumulation of toxins in the ashes, there are a total of 11 indicators including arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), iron (Fe), manganese (Mn) and selenium (Se). Analysis of toxic substances in ash begins with preparation of the ash sample. Follow the US EPA Test Methods for Evaluating Solid Waste, Physical/Chemical Methods (SW-846) by weighing 1.00 grams of ash sample, putting it into a 50 mL beaker, and adding mixed acid. (Concentrated nitric acid: perchloric acid = 2:1) volume 15ml. Dig on a hot plate in a fume hood until the solution is clear or the ashes contain a pasty white color of silica. Continue to digest until the white smoke disappears. Leave it to cool and then filter it with No. 42 filter paper. Adjust the volume to 50 ml with deionized water (DI) [14]. After that, the solution obtained from preparing the ash sample is analyzed for the amount of heavy metals with an Inductively Couple Plasma machine-Optical Emission Spectrometer (ICP-OES).

Economic analysis of conversion.

Cost-benefit analysis of RDF processing using cost analysis, break-even point and internal rate and economic feasibility analysis, net present value (NPV), benefit-cost ratio (BCR), and internal rate of return (IRR) are evaluated and used as indices for project evaluation [15,16].

3. Results and Discussion

Results of analysis of agricultural waste material properties

The study of agricultural waste properties, including rubber wood chips (RWC), wood residues (WR), mixed grass (MG), cassava rhizome (CR), and leaf fragments (LF) found that the heating value of agricultural waste materials was in the range of 14,693-17,065 kJ/kg, the energy value was in the range of 3,509.36-4,075.91 kcal/kg, the moisture content was in the range of 10.35 – 16.80 % and the density was in the range of 310.00 – 550.00 kg/m^3 as shown in table 1. The analysis results showed that the properties of the agricultural wastes were consistent with the research results of many researchers, especially the values of heating value, energy value, and density value which are the properties of biomass necessary for the conversion of agricultural materials into RDF [17, 18]. Therefore, all the agricultural waste materials are possible and suitable to be converted into RDF fuel.

Table 1 Test results of agricultural waste materials obtained from agricultural waste.

Sample	Heating value (kJ/kg)	Energy value (kcal/kg)	Moisture (%)	Density (kg/m^3)
Rubber wood chips (RWC)	17,065 ± 0.03	4,075.91 ± 0.05	15.55 ± 0.02	550.00 ± 0.05
Wood residues (WR)	14,693 ± 0.04	3,509.36 ± 0.02	16.80 ± 0.03	455.00 ± 0.04
Mixed grass (MG)	14,751 ± 0.02	3,523.22 ± 0.03	10.35 ± 0.01	310.00 ± 0.02
Cassava rhizome (CR)	16,587 ± 0.06	3,961.74 ± 0.02	16.20 ± 0.02	380.00 ± 0.01
Leaf fragments (LF)	16,723 ± 0.02	3,994.22 ± 0.01	12.45 ± 0.02	325.00 ± 0.03

note; * Biomass fuel properties values Department of Alternative Energy Development and Energy Efficiency, (2011) [18].

Physical and chemical properties of fuel briquettes from agricultural waste materials

From the study of fuel briquettes made from each type of agricultural waste and binder (cassava starch sludge and latex rubber) with a ratio of 0.50:0.50, it can be formed into strong cylindrical pellets. The surface is smooth and even. They have a diameter of 5.00 cm and a length of approximately 6.00- 12.00 cm, as shown in Fig. 2. It was found that the moisture contents were in the range of 7.56-8.32 wt.%. Fuel heat contents were in the range of 3,474.50 - 4,245.65 kcal/kg. Density values were in the range of 0.45 - 0.78 g/cm^3. Ash contents were in the range of 1.06 - 5.00 wt.%. Shatter index 0.71- 0.93. Ignition time of 5.6 - 9.8 min. The fuel burns for 30 - 96 min and the burning rate was 1.38 - 1.74 g/min, as shown in Fig. 3 and Table 2, From the study, it was found that the fuel pellets from agricultural waste materials have characteristics and properties that are consistent with the results of the waste transformation into RDF of the researcher, especially the values of calorific value, ash content, and density [12, 19, 20]. In addition, the solid fuel pellets follow the standard of the biomass fuel industry of Thailand [6].

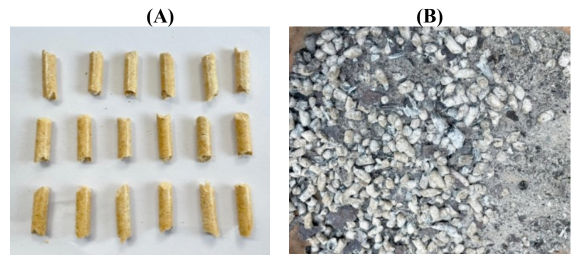


Fig. 2 (A) Characteristics of solid fuel from rubber wood scraps (B) Characteristics of ash from burning ash of fuel.

It also found a similar value to the research results on the comparison of the efficiency of compressed fuel from agricultural waste materials. The analysis results showed that the moisture content of agricultural waste materials was 6.00 - 8.33 wt.% and ash content of 2.67-12.67 wt.% [19], while the fuel calorific value is in the range 2,876.11 - 4,210.40 kcal/kg The density of the fuel rods is similar to that from the study of durian peel extrusion [12] which has the density of 0.74 g/cm^3. The quantity of the ash generated in the smallest fuel is the leaf fragments and binders equal to 1.06-1.07 wt.% [20]. The most common ash estimate is the fuel of rubber wood chips with the binder equal to 4.75-5.00 wt. %. In which the amount of ash produced. The smaller the amount of ash, the more efficient the fuel [11,12]. The efficiency comparison of fuel briquettes from agricultural wastes has the highest fracture index value of 0.99.

The ignition and the rate of fuel combustion are similar to the results from the study of energy fuel briquette production from sawdust of rubber wood, which has a test for combustion properties of compressed fuel, sawdust, wood, rubber, and animal dung with the amount of 10 combustion times. The combustion rate of the fuel is in the range of 6.28-11.70 min and 40.90-82.89 min respectively and the combustion rate is in the range of 1.17-1.80 g/min [6]. The results of the study are close to those of the research [21]. The maximum fracture index is 0.986, the ignition time is 8.4 min. The maximum combustion rate is 0.95 g/min. Comparing with the standard values and past research, it was found that sawdust is the best processing fuel. Compressed fuel made from waste rubber wood with latex as the adhesive, with a moisture content of 7.68 wt.% and a fuel calorific value of 4226.59 kcal/kg, with an ash content of 5.00 wt.%. These meet the standards for charcoal stick community products. The standard values for moisture content and ash content are at most 8 wt.%. Moisture content affects the density. The calorific value and combustion efficiency of compressed charcoal [22].

Heavy metals in ash from the fuel combustion including cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), iron (Fe), manganese (Mn), and selenium (Se) were all within the standard criteria of the Pollution Control Department of Thailand, as shown in Table 3. It can be concluded that the properties of RDF from the experiment are suitable for use as fuel in various industrial plants, such as rubber processing plants, biomass power plants, cassava starch processing plants, and sugar factories. [23,24,25,26,27].

Cost-benefit analysis results of RDF processing

Cost-benefit analysis of cassava rhizome processing, based on the quantity of cassava rhizome 882 kg/rai, by comparing two cases: farmers collect and sell the rhizome directly to the factory; farmers process RFD and sell to the factory. In case 1, the total cost was 0.07 baht/kg, it could be sold to the factory for 300 baht/ton (0.3 baht/kg).

Therefore, the profit of selling RDF fuel to rubber processing plants at the price of 1,000.00 baht/ton (1.00 baht/kg) [28] is 0.57 baht/kg or 504.22 baht/rai.

4. Conclusion

From this research, it can be concluded that the agricultural waste materials used in the experiment in the process of converting solid fuel (RDF) can be used as a renewable energy source. The actual test results found that RDF can provide the appropriate energy value according to the properties of biomass energy [2,5,6,]. Importantly, this RDF is also in demand by industrial factories in Loei Province, especially rubber drying factories and biomass power plants, etc. [23,24,25]. Furthermore, which is considered a new important discovery, is that rubber glue is a binder in the RDF processing process, and rubber glue has better adhesion properties than glue from cassava starch that many researchers currently use in FRD processing [12,19,20].

It can be summarized as follows: Compressed fuel from rubber wood chips mixed with the binder at a ratio of 0.50: 0.50 or 1.00:1.00 [29,30,31]. The rubber latex as the binder with the ratio of 1.0:20.0 (rubber latex to water) is the most effective. It has a moisture content of 7.68 wt.% and an ash content of 5.00 wt.%. This complies with the carbonated community products. It has an average calorific value of 4,226.59 kcal/kg [29], a density of 0.78 g/cm^3, a shatter index of 0.74, an ignition time of 5.6 min, a burning distance of 96 min. and a combustion rate of 1.74 g/min. From the analysis of heavy metals in ashes from combustion RDF, the amount of the heavy metals are within the community products standard. This shows that RDF fuel from agricultural waste materials can be used as fuel or alternative energy in industries that use oil or natural gas as fuel, thus reducing production costs for entrepreneurs [23,24,25,27]. It can also reduce greenhouse gas emissions from the agricultural sector in another way[2,11]. In addition, RDF is another alternative to sustainably increase income for farmers in Loei Province.

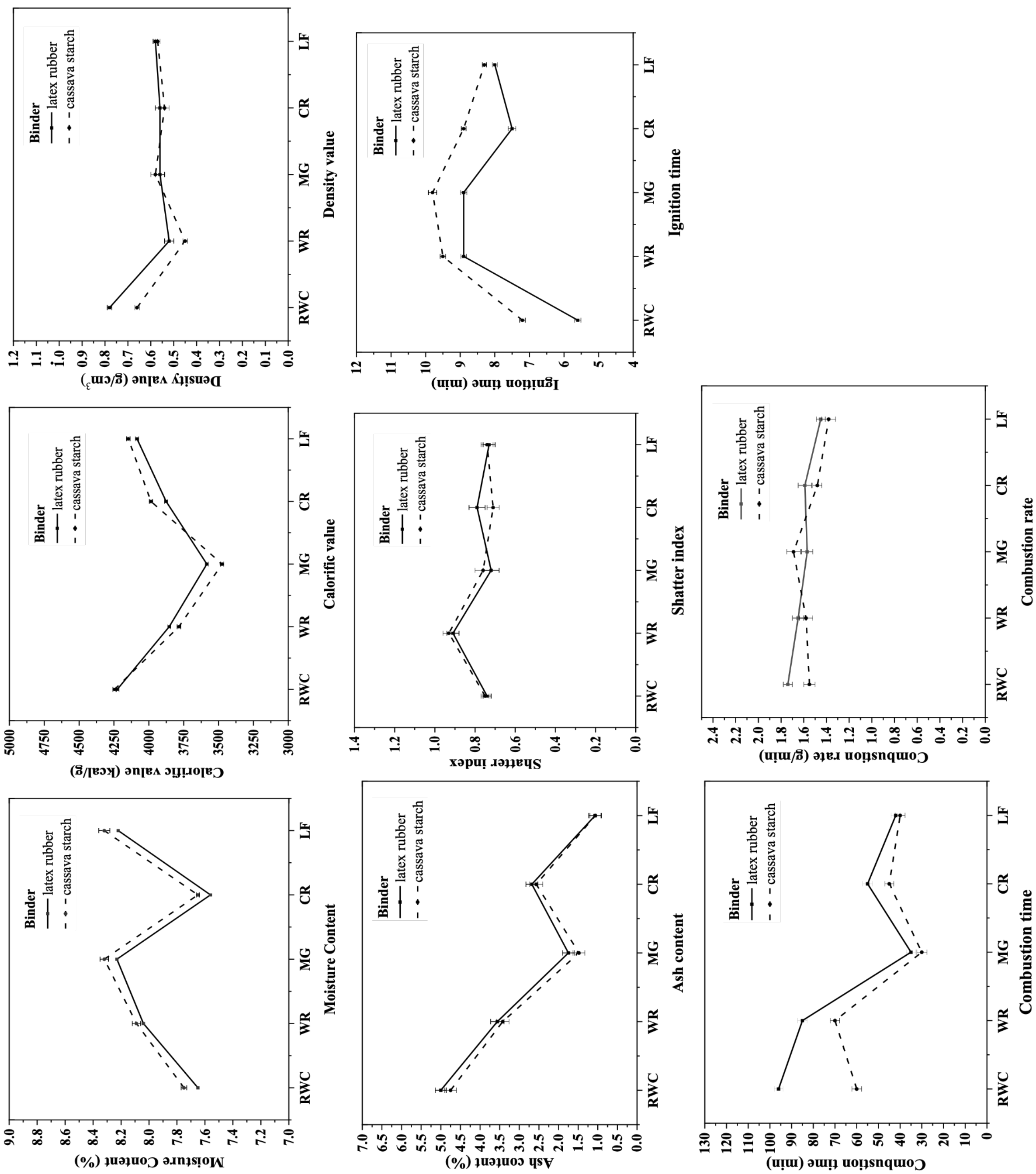


Fig. 3 Physical and chemical properties of good formable briquettes of each type of agricultural waste and binders.

Table 2 Potential effectiveness of different RDF binders.

Fuel briquette property	Binder	Moisture Content (%)	Energy value (kcal/kg)	Energy value (kg/cm^3)	Ash content (%)	Shatter index	Ignition time (min)	Combustion time (min)	Combustion rate (g/min)
Rubber wood chips (RWC)	Latex rubber	7.68± 0.02	4,226.59± 0.12	0.78± 0.01	5.00± 0.14	0.74± 0.02	5.60± 0.09	96.00± 0.06	1.74± 0.04
	Cassava starch	7.75± 0.02	4,245.65± 0.12	0.66± 0.01	4.75± 0.15	0.75± 0.02	7.20± 0.08	60.00± 0.07	1.55± 0.05
Wood residues (WR)	Latex rubber	8.04± 0.04	3,854.05± 0.10	0.52± 0.02	3.56± 0.17	0.91± 0.03	8.90± 0.08	85.00± 0.05	1.65± 0.05
	Cassava starch	8.09± 0.03	3,784.48± 0.11	0.45± 0.01	3.42± 0.16	0.93± 0.03	9.50± 0.08	70.00± 0.04	1.58± 0.06
Mixed grass (MG)	Latex rubber	8.23± 0.02	3,584.26± 0.12	0.56± 0.02	1.75± 0.15	0.72± 0.04	8.90± 0.09	35.00± 0.04	1.57± 0.05
	Cassava starch	8.32± 0.03	3,474.50± 0.12	0.58± 0.02	1.48± 0.15	0.76± 0.04	9.80± 0.12	30.00± 0.06	1.69± 0.06
Cassava rhizome (CR)	Latex rubber	7.56± 0.02	3,876.24± 0.10	0.56± 0.02	2.68± 0.15	0.79± 0.04	7.50± 0.11	55.00± 0.07	1.59± 0.06
	Cassava starch	7.65± 0.01	3,984.59± 0.10	0.54± 0.02	2.57± 0.17	0.71± 0.03	8.90± 0.07	45.00± 0.04	1.48± 0.04
Leaf fragments (LF)	Latex rubber	8.22± 0.02	4,084.99± 0.12	0.58± 0.01	1.07± 0.16	0.73± 0.03	8.00± 0.07	42.00± 0.05	1.45± 0.04
	Cassava starch	8.32± 0.04	4,147.36± 0.12	0.57± 0.01	1.06± 0.14	0.74± 0.03	8.30± 0.06	40.00± 0.04	1.38± 0.06

Table 3 Heavy metals content of the ash.

Biomass	**Binders**	**(pH)**	**Heavy metals content of the ash (mg/kg)**									
			As	**Cd**	**Pb**	**Cr**	**Cu**	**Zn**	**Fe**	**Mn**	**Ni**	**Se**
Rubber wood chips (RWC)	Latex rubber	6.90± 0.01	ND	ND	ND	ND	0.415± 0.02	0.258± 0.02	3.015± 0.04	1.235± 0.05	ND	8.654± 0.08
	Cassava starch	7.10± 0.02	ND	ND	ND	ND	0.418± 0.02	0.324± 0.03	3.333± 0.06	1.112± 0.04	ND	7.569± 0.04
Wood residues (WR)	Latex rubber	6.80± 0.02	ND	ND	ND	ND	0.393± 0.02	0.341± 0.06	3.328± 0.04	1.027± 0.03	ND	7.288± 0.02
	Cassava starch	6.60± 0.01	ND	ND	ND	ND	0.264± 0.01	0.362± 0.02	3.645± 0.10	1.035± 0.04	ND	6.589± 0.03
Mixed grass (MG)	Latex rubber	6.80± 0.02	ND	ND	ND	ND	0.476± 0.03	0.330± 0.03	3.554± 0.05	1.214± 0.05	ND	8.259± 0.05
	Cassava starch	7.10± 0.01	ND	ND	ND	ND	0.479± 0.03	0.321± 0.05	3.259± 0.05	1.345± 0.05	ND	7.368± 0.04
Cassava rhizome (CR)	Latex rubber	6.90± 0.02	ND	ND	ND	ND	0.418± 0.04	0.364± 0.01	3.596± 0.04	1.203± 0.05	ND	9.559± 0.04
	Cassava starch	7.10± 0.01	ND	ND	ND	ND	0.598± 0.04	0.408± 0.01	3.226± 0.03	1.245±0.02	ND	9.925± 0.05
Leaf fragments (LF)	Latex rubber	6.90± 0.02	ND	ND	ND	ND	0.385± 0.02	0.394± 0.02	3.254± 0.04	1.128± 0.06	ND	8.293± 0.04
	Cassava starch	6.80± 0.02	ND	ND	ND	ND	0.446±0.02	0.394± 0.04	3.289± 0.05	1.240± 0.04	ND	8.288± 0.06
Standard level		-	3.9	3.7	400	300	31.60	121.00	>20,000	1,800	1,600	390

ND : Non detection

5. Suggestions

To provide enough quantity of the fuel to the industry, we need to form the farmer groups as a network of community enterprises. With large quantity of the agricultural waste, the unit transportation costs can be reduces. The studies of processing RDF from other agricultural waste such as corncobs sugarcane leaves, straw, should be done to reduce incineration and make more income for farmers.

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7. References

[1] A. Białowiec, M. Micuda, J.A. Koziel, Waste to Carbon: Densification of Torrefied Refuse-Derived Fuel, Energies. 11(11) (2018) 3233. 10.3390/en11113233.

[2] C. Nobre, C. Vilarinho, O. Alves, B. Mendes, M. Gonçalves, Upgrading of refuse-derived fuel through torrefaction and carbonization: Evaluation of RDF char fuel properties, Energy.181 (2019) 66-76.

[3] M. Kara, Environmental and economic advantages associated with the use of RDF in cement kilns, Resources, Conservation and Recycling. 68 (2012) 21-28.

[4] H. Rezaei, F. Yazdan Panah, C.J. Lim, S. Sokhansanj, Pelletization of refuse-derived fuel with varying compositions of plastic, paper, organic and wood, Sustainability. 12(11) (2020) 4645. 10.3390/su12114645

[5] R. García, M. D. P. González-Vázquez, F. Rubiera, C. Pevida, M. V. Gil, Co-pelletization of pine sawdust and refused derived fuel (RDF) to high-quality waste-derived pellets, Journal of Cleaner Production. 328 (2021) 129635. 10.1016/j.jclepro.2021.129635

[6] W. Supranee, T. Nuchlee, Study of Energy Fuel Briquettes production from Sawdust of Rubber Wood and Animal Dung, UTK RESEARCH JOURNAL. 9 (2018).

[7] C. Kumpapai, N. Boonthanom, T. Rodjananon, J. Wongthanate, The Efficiency Comparison of Fuel Briquettes from Agricultural Wastes, The Journal of Industrial Technology. 16(3) (2020) 28-38.

[8] I. Batool, S. Munir, A. Khalid, A. Tahir, Potential Effectiveness of Different RDF Binders from Agro Waste, Technical Journal of University of Engineering & Technology Taxila. 26(1) (2021).

[9] K. Paopongpaiboon, K. Boonserm, V. Horsakulthai, Development of mechanical and physical properties of charcoal briquettes from rubber seeds mixed with coconut shells as alternative energy, Journal of Engineering and Innovation. 16(1) (2023) 158-167.

[10] Y. Yang, R. K. Liew, A. M. Tamothran, S. Y. Foong, P. N.Y. Yek, P. W. Chia, T. V. Tran, W. Peng, S. S. Lam, Gasification of refuse-derived fuel from municipal solid waste for energy production: a review, Environmental chemistry letters. 19 (2021) 2127-2140. 10.1007/s10311-020-01177-5

[11] N. Tangmankongworakoon, The production of fuel briquettes from bio-agricultural wastes and household wastes, Journal of Science and Technology. 12 (2014) 66-77.

[12] C. Kumpapai, N. Boonthanom, T. Rodjananon, J. Wongthanate, The Efficiency Comparison of Fuel Briquettes from Agricultural Wastes, The Journal of Industrial Technology. 16(3) (2020) 28-38.

[13] ASTM Standard D5865 International. (2013). *Standard Test Method for Moisture in the Analysis Sample of Coal and Coke*. ASTM International.

[14] ASTM Standard D3173 International. (2013). *Standard Test Method for Moisture in the Analysis Sample of Coal and Coke*. ASTM International.

[15] A. Awgichew, R. Nuguse, Development of Animal Feed Pellet Making Machine, Development. 7(1) (2024) 135-145.

[16] N. Srisaeng, N. Tippayawong, K. Y. Tippayawong, Energetic and economic feasibility of RDF to energy plant for a local Thai municipality, Energy Procedia. 110 (2017) 115- 120.

[17] Aliyu, M., et al. Production of composite briquettes (orange peels and corn cobs) and determination of its fuel properties. 2020. CIGR.

[18] ASTM Standard D3174 International. (2013). *Standard Test Method for Moisture in the Analysis Sample of Coal and Coke*. ASTM International.

[19] N. Tanpaiboonkul, T. Budnumpetch, Molding and Binding Method on Properties of Fuel from Water Hyacinth, Veridian E-Journal, Science and Technology Silpakorn University. 3(6) (2016) 86-100.

[20] V. Thathong, N. Tantamsapya, C.Yossapol, C. H. Liao, W. Wirojanagud, S. Padungthon, Role of Colocasia esculenta L. schott in arsenic removal by a pilot-scale constructed wetland filled with laterite soil, Heliyon. 5(2) (2019). 10.1016/j.heliyon.2019.e01233

[21] W. Punin, Development of Briquette Fuel from Co-Production of Corn Cob Charcoal and Low-Grade Coal Lignite Rejects, Burapha Science Journal. 23(1) (2018) 146-163.

[22] S. Kittikorn Sasujit, S. Warapong, W. Nattapong, D. Natthawud, Study of Process Densification of Corn Cob and Corn Husk Briquettes by Cold Extrusion Technique Using Starch with Lime Mixed as Binder, Thaksin. J..8 (1) (2015) 5-14.

[23] T. Gebreegziabher, A.O. Oyedun, H.T. Luk, T.Y.G. Lam, Y. Zhang, C.W. Hui, Design and optimization of biomass power plant, Chemical Engineering Research and Design. 92(8) (2014) 1412-1427.

[24] S. M. Shafie, T. M. I. Mahlia, H. H. Masjuki, A. Ahmad-Yazid, A review on electricity generation based on biomass residue in Malaysia, Renewable and Sustainable Energy Reviews. 16(8) (2012) 5879-5889.

[25] L. Thep-On, S. Chowdhury, K. A. Taechato, A. Kumar, I. Chanakaewsomboon, Optimization of biomass fuel composition for rubber glove manufacturing in Thailand, Sustainability. 14(19) (2022) 12493.

[26] V. Van Giau, T.T. Kien, T. Van Thanh, T.T Hieu, N.T.P. Thao, L.T. Son, T.L. Luu, H. Schnitzer, L.T. Hai, The role of specific energy consumption in a heat recovery system for cassava starch production using an integrated agro-industrial system, Energy, Sustainability and Society. 14(1) (2024) 43.

[27] N. Mohan, A.K. Kanaujia, Biomass energy for economic and environmental sustainability in India, Sugar Tech. 21(2) (2019) 197-201.

[28] Thai Industrial Standards Institute (TISI), M.o.I., SOLID BIOFUELS - BIOMASS PELLET 2019.

[29] A. Ussawarujikulchai, C. Semsayun, N. Prapakdee, N. Pieamsuwansiri, N. Chuchat, Utilization of durian and mangosteen peels as briquette fuel, 49 th Kasetsart University Annual Conference, Bangkok (Thailand). 1-4 Febuary 2011.

[30] L. Nyathi, G. Charis, M. Chigondo, M. Maposa, D. Nyadenga, K. Nyenyayi, Fabrication of sawdust briquettes using local banana pulp as a binder, Detritus. 19 (2022) 84-93. 10.31025/2611-4135/2022.15193

[31] R. N. P. Kiattisak, S. Tussanee, M. Chaiyoot, R. Polphat, Prototype System for Production of Refuse Derived Fuel (RDF-5) from Municipal Solid Waste Using Natural Rubber as Binder, ASEAN Journal of Scientific and Technological Reports. 26(3) (2023) 63-71. 10.55164/ajstr.v26i3.249665