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Valorisation of Rice Husk and Bubble Wrap Plastic Wastes through Co-Torrefaction to Optimise Biochar Production

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ABSTRAK

Kulit padi merupakan salah satu limbah pertanian dengan timbulan yang diperkirakan berjumlah 11,1-13,8 juta ton pada tahun 2021 di Indonesia. Timbulan ini membuat kulit padi menjadi salah satu biomassa potensial untuk dikonversi menjadi energi untuk meminimalisasi dampak negatif pengolahan eksisting berupa pembakaran dan penggunaan sebagai mulsa. Torefaksi dilakukan pada suhu 300^{0}C selama 30 menit dalam penelitian ini untuk meningkatkan karakteristik bahan bakar biomassa dengan menghasilkan *biochar* yang mempunyai karakteristik bakar lebih baik. *Biochar* yang dihasilkan dari torefaksi kulit padi memiliki nilai kalor 15,04 MJ/kg dengan kadar volatil 42,94% dan kadar karbon tetap 17,94%. Meski terjadi peningkatan karakteristik bahan bakar dibandingkan dengan kulit padi mentah, *biochar* ini cenderung memiliki hilang massa yang cukup tinggi dengan mass yield sebesar 54% saja. Oleh karena itu, penambahan umpan plastik LDPE dalam bentuk *bubble wrap* dilakukan hingga 50% massa umpan dan didapatkan optimasi lebih lanjut pada variasi RH50 dengan adanya peningkatan nilai kalor menjadi 19,98 MJ/kg dan *mass yield* menjadi 72%. Perubahan ini diuji dengan statistik dan bersifat signifikan, sehingga torefaksi merupakan suatu bentuk teknologi yang menjanjikan untuk pengolahan kulit padi, serta *bubble wrap* dalam penelitian ini dapat berperan signifikan dalam membantu meningkatkan karakteristik kulit padi sebagai bahan bakar.

Kata kunci: ko-torefaksi, kulit padi, bubble wrap, biochar, *waste-to-energy*

ABSTRACT

Rice husk is one of the highest generated agricultural waste estimated to be 11.1-13.8 million tons in Indonesia in 2021. This quantity makes rice husk a potential biomass for conversion into energy to minimize the negative impacts of current processing methods, such as open-burning and mulching. Torrefaction was conducted at 300°C for 30 minutes in this study to enhance the characteristics of biomass fuel by producing biochar with improved combustion properties. The biochar produced from torrefaction of rice husk has a calorific value of 15.04 MJ/kg with a volatile matter content of 42.94% and fixed carbon content of 17.94%. Despite this improvement compared to raw rice husk, this biochar tends to have a relatively high mass loss, with a mass yield of only 54%. Therefore, the addition of LDPE plastic feedstock in the form of bubble wrap was carried out up to 50% of the feedstock mass, resulting in further optimization at the RH50 variation, which increased the calorific value to 19.98 MJ/kg and mass yield to 72%. These changes were statistically tested and found to be significant, indicating that torrefaction is a promising technology for rice husk processing, and bubble wrap in this study can significantly contribute to enhancing the characteristics of rice husk as a renewable fuel source

Keywords: co-torrefaction, rice husk, bubble wrap, biochar, waste-to-energy

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1. Introduction

Rice husk is a byproduct of rice production, which is a staple food for the people of Indonesia. At least 11.1-13.8 million tons of rice husk waste is produced yearly in 2021 (Gidde & Jivani, 2007). With such great amount of waste produced, only 20% or less of the rice husk waste is valorised or treated to give additional value, meanwhile the remaining 80% is openly burnt or simply incorporated into the agricultural land. These two treatment can potentially impose negative impacts onto the environment through air pollution and reduction of environmental aesthetics by open burning and the potential of paddy disease caused by the incorporation of rice husk onto the soil (Goodman, 2020). Rice husk is a type of lignocellulosic biomass that has the potential to be made into fuel due to its high calorific value and its relatively lower moisture content when compared to other kind of biomass (Wantaneeyakul, Kositkanawuth, Turn, & Fu, 2021). Even then, rice husk still has the typical properties of biomass, which are, hydrophilic which makes it vulnerable to putrefaction, and also having lower bulk density which makes it rather economically unfeasible to transport and store.

Valorisation of waste is defined as the process of adding value to different types of wastes that are typically not treated in its existing scope of management, which might possess negative implications towards the environment (Ning, et al., 2021). One known method that can improve the potential of rice husk utilisation as a source of energy is through the thermochemical conversion process of torrefaction. Torrefaction is a endothermic process done in an inert atmosphere at 200-300°C on atmospheric pressure with a slow heating rate of less than 50°C/min which is a condition engineered to optimise the production of biochar (solid fuel) from different kinds of raw material, especially biomass. During torrefaction, devolatilisation, dehydrogenation, and deoxygenation reactions occur which cause the loss of volatile matters with lower calorific value which leaves the biomass matrix in the form of gases like CO_2, H_2O, and other non-condensable gases. Aside from that, the wide destruction of hemicellulose within the biomass at 200-230°C, which is the main intracellular water retainer, causes the char to be more hydrophobic when compared to the raw material. Also, along with the increase in torrefaction holding temperature, the calorific value of the char increases.

However, the increase in calorific value during torrefaction and subsequently the operation temperature, come at a cost of the increasing mass loss which becomes higher as the duration and temperature of torrefaction is increased. Furthermore, the majority of rice husk is comprised of holocellulosic polymers (cellulose and hemicellulose) which is widely depolymerised and 250-300°C. This problem calls for an enhancer, which should be added to increase the feasibility of the energy utilisation of such abundantly available biomass.

One type of enhancer is *low-density polyethylene* (LDPE) plastic. LDPE plastic has been used before in a research as a mixture in the torrefaction of mango branch and newspaper with satisfactory results in terms of its energy yield and its biochar product physicochemical characteristics. This satisfactory result is produced at 50:50 weight ratio of biomass and LDPE (Rago, Collard, & Mohee, 2020).

The usage of plastic as a biochar production enhancer is also considerably environmentally beneficial due to reducing the amount of plastic waste. It is known that during the COVID-19 pandemic, the generation of plastic waste is also increased due to the world requiring more and more single-use plastic. Furthermore, it is also projected that in the future, the usage of plastic is still growing year-by-year. LDPE is also known to have higher calorific value (43-45 MJ/kg), which makes it very feasible for energy recovery purposes and it has a lower recycle rate compared to PET and HDPE (Klemeš, Fan, Tan, & Jiang, 2020). In this research, bubble wrap plastic waste from online shopping is used. Bubble wrap is typically produced using LDPE resin.

According to the literature review conducted, co-processing of rice husk and bubble wrap wastes is predicted to be feasible. The co-torrefaction is aimed to increase the fuel properties of rice husk, decrease mass loss, increase calorific value of rice husk, and the reduction of agricultural and plastic waste in general. Due to the mentioned problems above, this study aims to: (1) identify the ideal mixture ratio of rice husk and bubble wrap to optimise biochar production and (2) identify the increase in fuel properties among different rice husk feeds (raw, torrefied, and co-torrefied). This study is limited to only analysing the approximate fuel characteristics of rice husk biochar made from torrefaction alongside bubble wrap (LDPE) plastic waste, which then will be analysed descriptively using Indonesian standard for Refuse-Derived Fuel (RDF) due to the absence of biomass-specific fuel standard as of the time of writing this paper.

2. Methods

2.1. Sample Preparation

Sample of rice husk was obtained from agricultural land located in Lembang, West Java in February 2022, while sample of bubble wrap plastic was obtained from online shopping packaging, which was manually shredded and sieved on no. 20 mesh size. The samples were dried in the oven for 24 hours at 105°C before torrefied. It is then stored inside desiccated plastic bags to prevent re-moisturization.

2.2. Torrefaction

The production of the biochar from biomass and plastic mixture is done using Thermolyne Tube Furnace Model 21100 at 300°C and a heating rate of 10°C/minute, so that slow pyrolysis condition was created. The atmosphere within the reactor was purged continuously using nitrogen gas (N_2) with a flow rate of 1.0 L/minute measured using a rotameter. The feedstock has 6 variations of pre-determined ratio. The variation of feedstock ratio was used to identify the effect of bubble wrap (BW) plastic addition to the quality of physicochemical characteristics of rice husk (RH) biochar. The variation of feedstock is shown in **Table 1.**

Table 1. Variation of feedstock composition

Sample	Rice Husk (wt%)	Bubble wrap (wt. %)
RH100	100	0
RH90	90	10
RH80	80	20
RH70	70	30
RH60	60	40
RH50	50	50

The feedstock was weighed pre-production to the nearest 0.0001 gram using Fujitsu AR2100 analytical balance. The amount of feedstock used was 10±0.1000 grams and each variation was tested three times to determine reproducibility of results, amounting to 18 total runs. **Figure 1** illustrates the schematic diagram of torrefaction setup used in the production phase.

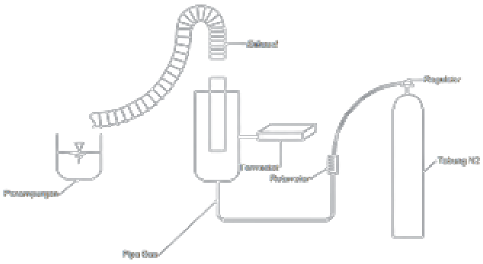

Figure 1. Schematic diagram of torrefaction reactor

2.3. Characterization of Feedstock and Biochar

Characterisation of proximate and calorific value analyses parameters were done according to the ASTM standard methods shown in **Table 2**.

Table 2. ASTM methods for proximate analysis

Parameter	Feedstock type	
	RH	BW/Biochar
Proximate Analysis	E870	D3172
Moisture	E871	D3173
Ash	D1105	D3174
Volatile Matter	E872	D3175
Fixed Carbon	E870	D3172
Cal. Value (HHV)	D2015	D2015

Feedstock characterisation was also done for ultimate analysis parameters of carbon (C), hydrogen (H), and oxygen (O). The ultimate analysis is done using an empirical formula based on the proximate analysis results developed by Nhuchhen & Salam, (2012). The equations used for the calculation of C, H, and O contents are listed on **Table 3**.

Lastly, calorific value was determined experimentally using PARR 1260 Bomb Calorimeter.

Table 3. Ultimate analysis proximation equations

Empirical Equation	Reference
$C = -35{,}9972 + 0{,}7698VM + 1.3269FC + 0.3205AC$	(Nhuchhen & Salam, 2012)
$H = 55{,}3678 - 0{,}4830VM - 0{,}5319FC - 0.5600AC$	
$O = 0{,}569VM + 0{,}010FC - 0{,}069AC$	

2.4. Mass Yield, Energy Yield, and Energy Density

The mass yield (MY), energy yield (EY), and energy density (ED) parameters were used to identify the effect of torrefaction onto the mass and energy contents of the biochar that were lost or gained due to the thermochemical conversion process. The following equations are used to calculate the three parameters mentioned.

$$MY_{db} = \frac{M_{torr}}{M_o} \qquad ED = \frac{HHV_{torr}}{HHV_o}$$

$$EY = \frac{M_{torr}}{M_o} \times \frac{HHV_{torr}}{HHV_o}$$

With:
MY_{db} = dry basis mass yield
M_{torr} = torrefied biomass weight (gram)
M_o = raw biomass weight (gram)
EY = energy yield
HHV_{torr} = calorific value of torrefied biomass (MJ/kg)
HHV_o = calorific value of raw biomass (MJ/kg)
ED = energy density

2.4. Statistical Analysis

Statistical analysis was carried out using one-way ANOVA in R version 4.2.3 to determine the significance of sample variations in influencing the properties of rice husk.

3. Results and Analysis

3.1. Feedstock characterisation

The following **Table 4** details the result of feedstock characterisation.

Table 4. Results of feedstock characterisation

Parameter	Rice Husk	Bubble Wrap
Proximate (wt. %)		
Moisture content	12.98	1.61
Volatile matter^{db}	67.53	97.20
Fixed carbon^{db}	6.22	2.13
Ash content^{db}	26.25	0.66
Ultimate (wt. %)		
Carbon (C)	32.52 – 34.69	83.29
Hydrogen (H)	4.42 – 4.74	16.71
Oxygen (O)	34.04 – 36.67	-
HHV (MJ/kg)	14.93	21.00

^{db}: dry basis

The characterisation of rice husk biomass is concluded to be valid due to the values being in the range of the referenced literatures (Anshar, Tahir, Makhrani, Ani, & Kader, 2018). Meanwhile, bubble wrap plastic has higher than usual moisture content and fixed carbon. This could be happening due to the absence of pre-treatment of bubble wrap by sun-drying the plastic to release the excess moisture perceived to be present in the storage box of the bubble wrap, which is rather damp. Furthermore, the calorific value of bubble wrap is also mismatched when compared to the literature, in which it only has approximately 50% of the expected value. This phenomenon could be attributed to the high amount of additives contained within the plastic, which could be due to the manufacturing process of bubble wrap using mixed plastic, instead of pure LDPE, or other contaminants sticking onto the surface of the bubble wrap plastic waste.

3.2. Biochar Morphology

Figure 2 details the shift in the appearance of the biochar along with the increase in bubble wrap plastic mass fraction within the torrefied feedstock. All of the biochar produced is black in colour, which is a match to other research like Chen, Zhou, Zhang, Zhu, & Lu, (2014), in which they also used 300^{o}C as the torrefaction temperature. The change in colour of rice husk from light brown to deep black is a result of the following reactions onto the biopolymer structure of rice husk, which are as follow.

- Devolatilisation & carbonisation of hemicellulose,
- Depolimerisation & softening of lignin,
- Depolimerisation & devolatilisation of cellulose.

Aside from that, the biochar characteristics have notably changed along with the addition of bubble wrap mass fraction within the feedstock. Biochar with higher plastic weight fraction has a higher rate of agglomeration, which is suspected to be caused by the molten plastic, further causing the char particles to stick onto each other and agglomerate into bigger, more resistant particle.

The resistance present in higher weight fraction variations of plastic in the feedstock makes it harder to grind into finer particle. On lower weight fraction of plastic in the feedstock (RH80 and RH90), the agglomeration is relatively lower and the char is still quite easy to grind when compared to other char (RH50, RH60, and RH70). RH80 and RH90 still possess the characteristics similar to RH100.

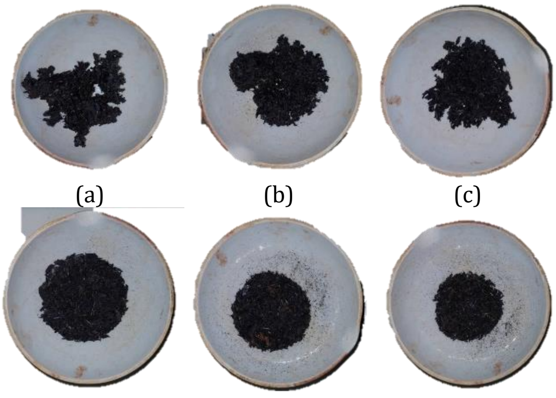
(a) (b) (c)
(d) (e) (f)

Figure 2. Biochar morphology of
(a) RH50; (b) RH60; (c) RH70; (d) RH80;
(e) RH90; and (f) RH100

3.3. Yield Analysis

Figure 3 shows the increase in mass yield, energy yield, and energy density of biochar along with the increase of plastic weight fraction within the torrefied feedstock.

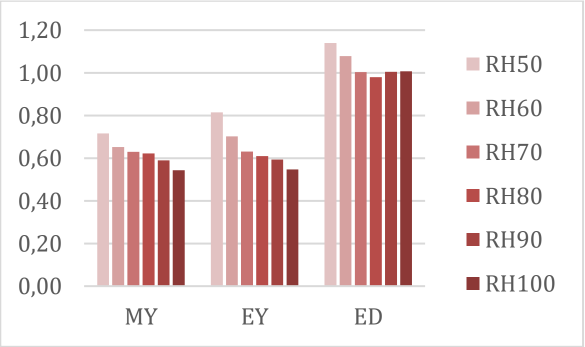

Figure 3. Yield analysis results

This result is in accordance with previous researches, in which it is found that the three parameters have increased in value along with the increase of plastic weight fraction in the feedstock (Wantaneeyakul, Kositkanawuth, Turn, & Fu, 2021; Rago, Collard, & Mohee, 2020). The loss of mass, as explained by one research, is caused by intensification of cracking reaction which produced more gaseous and liquid product (Chen, et al., 2018). Biochar mass yield increases as the amount of bubble wrap plastic within the feedstock is increased. The MY slowly increases from 0.54 to 0.72 from RH100 to RH50 respectively. The increase in MY is attributed to the plastic fraction not experiencing volatilisation like the biomass, which causes mass loss.

Energy yield produced by biochar along with the increase in weight fraction of plastic in the feedstock increases from 0.55 on RH100 to 0.81 on RH50. The decrease in energy yield is expected to happen and could be relatively high on rice husk due to its high percentage of hemicellulose and cellulose content which is thermally decomposed at 300^{o}C. As a result, the rate of calorific value increase is lower than rate of mass loss. From this result however, we can estimate that addition of bubble wrap plastic in the feedstock can mitigate the mass loss and energy yield loss.

Energy density from torrefaction of rice husk varies from 0,98 in RH80 to 1,14 in RH50. The energy density significantly jumped from RH70 to RH60 by 0.08 absolute value from 1.00 to 10.08. Energy density is also a parameter that shows relative biochar calorific value when compared to raw feedstock. As a result, torrefaction of RH100 causes a 1% calorific value increase, while RH50 provides 14% increase in energy.

3.4. Physicochemical Characterisation

3.4.1 Proximate Analysis

From **Figure 4**, it is known that torrefaction is able to increase the fuel properties of rice husk.

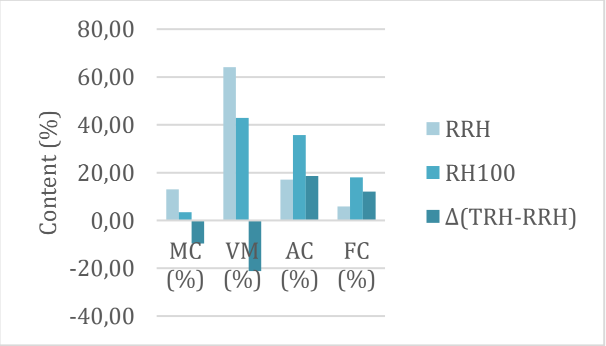

Figure 4. Proximate analysis results (RRH vs. RH100)

The increase in fuel properties of rice husk can be analysed from the increase in fixed carbon content (FC%) by 12,07%, decrease in moisture content (MC%) by 9,58%, and decrease in volatile matter content (VM%) by 21,16%. This finding is quite similar to other researches, in which the volatile contents of the char is significantly lower due to the high processing temperature (Wantaneeyakul, Kositkanawuth, Turn, & Fu, 2021; Chen, et al., 2018). The decrease in moisture content is due to decomposition of hemicellulose, the amorphous matrix storing water in its structure. The decrease in volatile matter content is also caused by the wide decomposition of hemicellulose and cellulose, and a tiny bit of lignin, especially structures containing phenol and acetic acid. As a result, fixed carbon content passively increases, which is expected to increase the flame duration of the produced biochar.

The decrease in volatile matter content would be attributed to the lower amount of smoke (Sadaka & Negi, 2009). Increase in ash content (AC%) of 18,68% could be attributed to the side effects of torrefaction, in which thermochemical conversion cannot decrease the amount of ash content within the biomass, which is comprised of mostly inorganic minerals. As a result, the absolute weight of ash remains relatively the same, but volatilised organics which leave the biomass matrix as gases count to the weight of the biomass. This causes the relative increase of ash content in torrefied biomass.

Figure 5 shows the changes in proximate analysis parameters along with the increase in bubble wrap weight fraction in the feedstock. From the graph, it can be identified that moisture content, ash content, and fixed carbon content tend to decrease with higher plastic weight fraction, while volatile matter content increases. These trends of proximate analysis is expected due to the addition of plastic which has lower fixed carbon, higher volatile matter, lower moisture, and lower ash content.

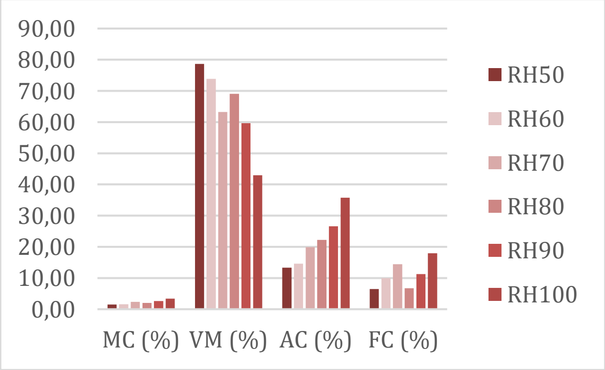

Figure 5. Proximate analysis result of each feed variation

Even though the volatile matter of biochar increases along with the increased weight fraction of plastic in the feedstock, the perceived negative impact would be neutralised by the fact that RH50 has the highest calorific value. The polymers contained within the plastic also has higher calorific value when compared to the rice husk's volatile matter (especially those from the volatilised hemicellulose and cellulose matrices).

3.4.2 Ultimate Analysis

Figure 6 describes the changes in percentages of carbon, hydrogen, and oxygen content (weight) within the matrix of the biochar.

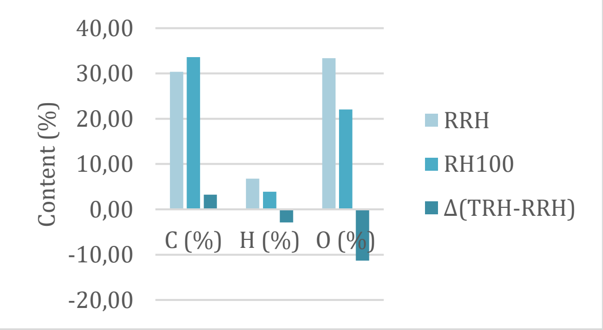

Figure 6. Ultimate analysis results (RRH vs. RH100)

From the graph, it can be inferred that carbon weight percentage increases by 3.24%, followed by reduction of hydrogen and oxygen weight by 2.87% and 11.33% respectively. The decrease in hydrogen and oxygen content within the biochar occurs due to devolatilisation, dehydrogenation, and deoxygenation of biomass during torrefaction. Torrefaction causes water/moisture and lower molecular weight compounds to volatilise and leave the biomass matrix. The resulting biochar has lower O/C and H/C ratio, which is comparable to lignite coal, sitting at 0.49 and 1.39 respectively (Loo & Koppejan, 2007).

Carbon and hydrogen are two factors that could increase the calorific value of a fuel, while oxygen decreases it. Oxygen content can also provide necessary oyxgen gas that is required in combustion. Hydrogen in general has higher calorific value dan carbon, but high hydrogen to carbon ratio could decrease the calorific value of the fuel (Adamovics, Platace, Kakitis, & Ivanovs, 2019). With the phenomenon shown in **Figure 6**, it can be concluded that torrefaction improves the fuel properties of rice husk due to it increasing carbon content, and decreasing oxygen and hydrogen contents.

Figure 7 shows the trend of changes in ultimate analysis parameters along with the increase in weight fraction of bubble wrap plastic in the feedstock. In the figure, it can be observed that the trend in carbon content increase is continued with higher plastic content. Hydrogen content is also increased, while oxygen content depletes. This could happen due to two factors, which are polymer composition of bubble wrap that is mostly consisting of C-H structure, which causes the addition in carbon and hydrogen content even in its raw form. The hydrogen and oxygen content still decrease, even though theoritically, hydrogen content in the feedstock is higher in high plastic weight fraction. This could mean that the reactions that happened still severely affected the hydrogen content of the polymer.

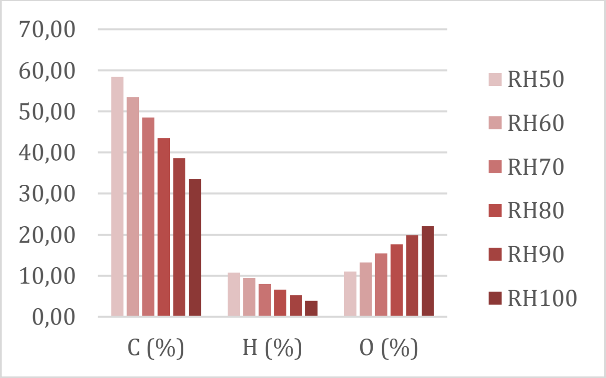

Figure 7. Ultimate analysis result of each feed variation

3.4.3 HHV Analysis

Figure 8 shows the change in calorific value from raw rice husk and torrefied rice husk (RH100).

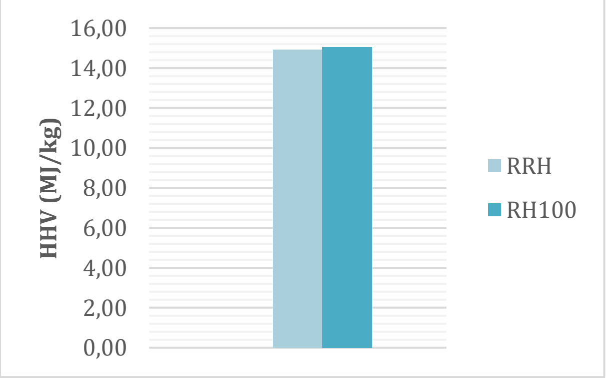

Figure 8. HHV analysis results (RRH vs. RH100)

From the graph, it can be observed that the calorific value of RH100 is 0.75% higher than RRH, or 0.11 MJ/kg in absolute numbers. The increase is relatively insignificant which could be attributed to the decrease in hydrogen content which contributes to the addition of calorific value within biochar. However, it can also be observed that the calorific value still increases, which indicates that carbon content within the biochar matrix contributes more towards the change.

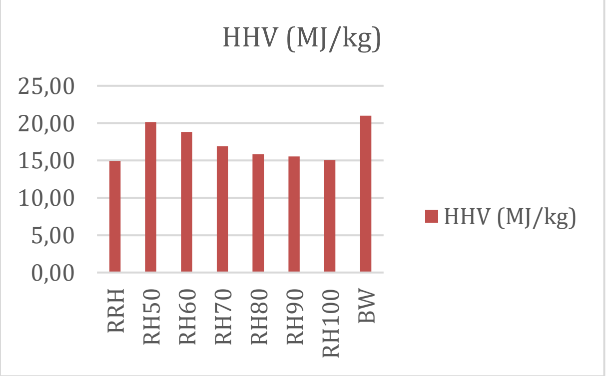

Figure 9. HHV analysis result of each feed variation

From **Figure 9**, it can be observed that calorific value of biochar increases along with the increase in the weight fraction of plastic in the feedstock. Experimental HHV increases from 15.04 MJ/kg for RH100 to 20.13 MJ/kg for RH50. A significant jump in calorific value increase occurs since RH70 onwards, which marks the first time that the experimental calorific value is higher than predictive HHV. As a result, it can be concluded that the increase in plastic fraction in the feedstock in can significantly increase the calorific value of the biochar.

3.5. Statistical Analysis

ANOVA was conducted to determine the effect of varying feedstock composition on 5 experimentally-determined parameters (MC, VM, AC, FC, and HHV) and it was found that all of these parameters are significantly affected by the variation as indicated by their p-value of less than 0.05. Several ANOVA diagnostics (Levene and Shapiro-Wilk Tests) were also run and confirmed that there was no assumption of ANOVA that was broken.

3.6. Comparison of Biochar Characteristics to Indonesian RDF Standards

The comparison of biochar characteristics to the RDF guidelines in Indonesia is based on the national standards contained in SNI 8966:2021 which standardises solid refuse-derived fuel. This comparison serves as a quality control to observe whether the biochar produced in this research can be feasibly utilised in industrial boilers as a fuel mix according to the imposed standards, for example utilisation in coal-fired powerplant. This comparative analysis is done onto RH100 and RH50 variations of biochar, which has been analysed to be in different extremes of proximate, ultimate, and calorific value analyses done previously.

From **Table 7**, it can be observed that RH100 biochar fulfills the criteria for class 1 fuel for moisture content, volatile matter, and fixed carbon parameters, while its HHV fulfills class 2 guideline, while its ash content is way beyond the standards for class 3 limits. On the other side, RH50 satisfies the class 1 standards for moisture content, ash content, and calorific value, while its fixed carbon content is classified into class 3, and volatile matter failing to be sorted into any class. The high ash content can be attributed to the existing ash content (26.25%) contained within the rice husk sample used. Along with the volatilisation of volatile matters within the rice husk, ash content remains the same due to the inability of thermal process to eliminate ash. This causes the ash content to relatively increase due to torrefaction.

In this research, analysis is not done on sulfur and chlorine content parameters. Even so, according to the characterisation of other researches onto rice husk chars from burner is estimated to be 0.03 and 0.036 wt.% respectively (Ankyu, Noguchi, & Kubota, 2017). Other than that, other researches also concluded that thermochemical conversion in inert condition (pyrolysis dan torrefaction) could actually decrease sulfur and chlorine content within the biomass matrix.

Thermochemical conversion causes significant reduction in sulfur content (60%) and moderate reduction in chlorine content (35%, released as methyl chloride gas, CH_3Cl) at 250-350^{o}C (Saleh, Shoulaifar, Flensborg, & Sarossy, 2014). As a result, it can be inferred that class 1 fuel quality can be achieved by RH50 And RH100 for both parameters.

Table 5. Comparison of biochar and RDF standard

Para-meter	Unit	Class			Experimental Data	
		1	2	3	RH 100	RH 50
Organic matter	%, min	≥95	87.5 - 95	80–87.5	-	-
MC (ar)	wt. %	<15	<20	<25	3.39	1.47
AC (ar)	wt. %	<15	<20	<25	35.73	13.34
VM (ar)	wt. %	65	70	75	42.94	78.68
FC (ar)	wt. %	>15	>10	>5	17.94	6.51
HHV (ar)	MJ/kg	≥20	≥15	≥10	15.04	20.00
S (ar)	wt. %	≤1.5	≤1.5	≤1.5	-	-
Cl(ar)	wt. %	≤0.2	≤0.6	≤1	-	-

ar : as-received basis

3.8. Impact Analysis

The problems in the implementation of using lignocellulosic biomass as a source of renewable energy are its high moisture content, low bulk density, hydrophilic properties, and low energy density. Torrefaction is one technological approach mainly researched as a pre-treatment for biomass to produce biochar for further/advanced utilisation as source of energy, for example as a mixture in co-firing purposes and gasification. Typically, torrefaction will decrease the affinity of ability of biomass to store water, increases grindability, densify energy, provide ease of transport and storage, and stop putrefaction caused by metabolism of microorganism on raw biomass.

The advantages provided by torrefied biomass (*biochar*) is that it prevents biomass putrefaction, which in turn increases the storage life of biomass fuel. Other than that, lower moisture content in torrefied biomass also means that it has higher value in net calorific value (lower heating value) contained within the biomass. The increase in grindability also means that the powderisation of torrefied biomass require less energy (by a factor of 3-7 times) when compared to raw biomass. Torrefaction is also known to densify energy by having lower volume and higher energy content. Transportation and storage of biomass are also made easier and cheaper due to both these sectors usually counted using volumetric units (Nunes, Matias, & Catalão, 2017).

In relation with the type of feedstock used in this research, rice husk is a lignocellulosic biomass byproduct of the staple food product, rice. As a result, the generation of rice husk waste will always be abundantly available, accounting 20% of the total weight of the paddy harvested from the fields (Gidde & Jivani, 2007). Rice husk is also known to not be treated responsibly, for example getting openly and uncontrollably burnt, while also disposed into the soil which damages the environment (Goodman, 2020). Combustion of biomass results in the production of pollutant like particulate matters and green house gases (CO_2 and CH_4), and aesthetically unpleasant smell. Disposal of rice husk waste into the soil can also cause soil degradation and cause paddy diseases in the next crop cycle (Hanafi, Khadrawy, Ahmed, & Zaabal, 2012). Low utilisation rate of rice husk of only around 20% worldwide (Goodman, 2020) also means that the usage of rice husk waste can be further commercialised, for example through the thermochemical conversion route which upgrades the fuel properties of rice husk waste for further usage in industrial boiler and power plants.

Furthermore, during this research, the writer has yet to find a specific treatment for bubble wrap waste. In accordance with the increase in packaging waste caused by modernisation of society and the COVID-19 Pandemic, the generation of bubble wrap is expected to increase in the foreseeable future. LDPE, the common resin used to produce bubble wrap is also known not to be widely recycled yet (Klemeš, Fan, Tan, & Jiang, 2020). Bubble wrap waste, and LDPE waste is typically discarded and/or left as is when its utilisation period as a packaging has elapsed. Torrefaction opens a new pathway for utilisation of bubble wrap waste as an optimising/enhancing agent for biochar production. However, this pathway still needs further research, especially due to the potential of reduction of plastic waste stream coming into the landfills, which can limit the environmental impact of antrophogenic activities. This potential has been demonstrated to work not only on bubble wrap, but also LDPE, HDPE, and PP which in general has higher calorific value (Wantaneeyakul, Kositkanawuth, Turn, & Fu, 2021; Rago, Collard, & Mohee, 2020).

4. Conclusion

Torrefaction was shown to increase several fuel properties of rice husk waste, and the addition of bubble wrap plastic had increased the improvement in fuel characteristics further by decreasing the moisture and ash content, while increasing the calorific value of the biochar among others. The optimum feedstock variation was RH50, in which the losses of energy shown in the energy yield parameter was minimized due to molten plastics blocking the pores of the biochar, thus limiting the devolatilization caused by severe torrefaction temperature of 300^{0}C. Further analyses can be made by adding variations of temperature and holding time, especially due to high hemicellulose and cellulose content in rice husk, which are very sensitive to degradation in higher temperature range of torrefaction.

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