EREM 79/3
Journal of Environmental Research, Engineering and Management
Vol. 79 / No. 3 / 2023
pp. 52–59
DOI 10.5755/j01.erem.79.3.33741

Torrefaction for Upgrading the Quality of Merbau Wood Waste Pellets

Received 2023/03 | Accepted after revisions 2023/06

https://doi.org/10.5755/j01.erem.79.3.33741

Torrefaction for Upgrading the Quality of Merbau Wood Waste Pellets

Johanes Pramana Gentur Sutapa[1]*, Gianova Vierry Prasetyadi[2]

[1] Department of Forest Product Technology, Faculty of Forestry, Universitas Gadjah Mada, Indonesia

[2] Research Team of J.P. Gentur Sutapa, Faculty of Forestry, Universitas Gadjah Mada, Indonesia

***Corresponding author:** jpgentursutapa@ugm.ac.id

Recently, biofuels are intensively studied regarding the need of alternative renewable energy sources. Woody biomass has been one of the raw materials which are used in various ways including biofuels. As for biofuels, woody biomass has yet to possess some disadvantages such as bulk dimension, low density, non-uniformity, and high moisture content. Pelletizing has been one of the ways to improve the quality of woody biomass to be a proper biofuel. However, wood pellets also still offer downside such as hygroscopicity. Torrefaction is one of the methods to upgrade pellets quality such as high calorific value, fixed carbon, and hydrophobicity. In this study, merbau wood waste pellets were dry torrefied at a temperature of 200°C and 250°C for 15 and 30 minutes. The data obtained showed that torrefaction applied on merbau wood waste pellets could produce high quality pellets.

Keywords: pellets, merbau, torrefaction.

Introduction

Recently, there are many various types of technology developments regarding the renewable energy. For instance, there are studies focusing on materials to support the continuity of renewable energy manufacture such as metamaterials for generating new enhanced materials (Kumar et al., 2022) and nanofluids utilized in distinct thermal applications on solar power generation (Goga et al., 2023). Furthermore, the source materials of renewable energy are also deeply studied. One of them is biofuel due to its promising potentials. Biofuel is plant biomass, and the refined products to be burned for energy exist in solid, liquid, and gaseous forms (Guo et al., 2014). Solid biofuels have existed in the form of wood chips, pellets, briqwuettes, etc. Liquid biofuels are developed in the form of biodiesel which can be derived from palm methyl ester (Procha et al., 2019), cotton seed oil (Chandel et al., 2016), coconut oil, castor oil, rice bran oil, etc. (Gupta et al., 2020), or in the form of bioethanol. Furthermore gaseous biofuels have existed in the form of biogas, biomethane, etc. The advantage of biofuel utilization is that emission from using biofuels is replaced by the carbon absorbed during the growth of the plant, hence, it is considered as a carbon neutral energy source (Mathews, 2008). Therefore, many researches were done in line with the development of biofuels.

Woody biomass has been used for plenty of ways. People have always utilized it for their needs such as farming tools, material for building, weapons, and fuels, whereas wood has been playing an important role on material construction and energy generation until the end of the 19th century (Owoyemi et al., 2016). As for energy generation, direct combustion has long been, and still is, the most common way of utilizing biomass (including wood) (Omer, 2012). Despite being widely used, woody biomass offers some disadvantages. Low density, non-uniformity on shapes and sizes, and high moisture content have been some of the most serious problems on utilizing solid biomass (such as woody biomass) for energy generation (Forero Núñez et al., 2012).

Densification could offer a solution for utilizing woody biomass. In comparison with untreated woody biomass, densified biomass, such as pellets, possesses lower moisture content, high bulk and energy density resulting in better longevity for storage, efficient energy, and advantages on transportation (Holm et al., 2006). Despite the flaws, pellets still possess disadvantages, for example, its high hygroscopicity which results in degradation when wetted (Craven et al., 2015). In order to overcome those disadvantages, some treatment could be applied to upgrade wood pellet quality.

Torrefaction is a treatment for solid biofuels to achieve an upgrade to the quality. Torrefaction exists in 2 types, dry torrefaction and wet torrefaction. Dry torrefaction is a torrefaction done in a dry and non-oxidative (inert) atmosphere or at a temperature of 200–300°C, while wet torrefaction is done by soaking in a water and acid solution at a temperature of 180–260°C (Chen et al., 2021). By torrefaction, decreased volatile matter, increased calorific value and hydrophobicity of biofuels can be achieved (Kumar et al., 2016). Moreover, torrefaction increases calorific value, thus improving thermal efficiencies (Bergman and Kiel, 2005). A previous study (Wang et al., 2020) reported an increase of calorific value, fixed carbon content, and hydrophobicity, but a decrease on the durability and tensile strength of several woody biomass pellets. Hence, torrefaction could be an alternative to increase the quality of wood pellets.

In this study, merbau wood wastes were used as a material for torrefied pellets. Merbau (*Intsia bijuga*) is a tree species originated from the Papua region, Indonesia. It has been reported that as much as 788,000 m^3 of merbau wood was exported by Indonesia in 2019–2021 (Betahita, 2020). Based on those numbers, it can be concluded that merbau wood has its own potential, specifically its wastes generated by the wood industries. This study was done in the direction of engaging advanced technology on producing high quality product, particularly high quality pellets from merbau wood wastes.

Methods

Resource materials

CV. Indo Jati Utama, a merbau wood industry located in Semarang city, Jawa Tengah Province, provided the sawdust waste of merbau (*Intsia bijuga*) wood.

Sample drying

Merbau wood sawdust waste was dried to a moisture content of ± 12%.

Pellets production

Prior to pelletizing, merbau wood sawdust was sieved to a size of 0.177–0.250 mm. The process of making pellets involved using a single pelletizer machine, specifically the Carver 2101 hydraulic press, with a pressure setting of 150 kg/m^2.

Torrefaction

Torrefaction was done using a Thermolyne furnace, with the temperature variation of 200°C and 250°C, and duration variation of 15 and 30 minutes.

Physical characterization of torrefied merbau wood pellets (TMWP)

The physical properties of the pellets were assessed by measuring their compressive strength using a Universal Testing Machine. The maximum force of compression applied before the pellets failed, with the same weight (N), was recorded as the compressive strength (COM), following the guidelines of ASTM D4179-01.

Proximate characterization of TMWP

The proximate analysis of the sample involved measuring its moisture content (MC), volatile matter content (VMC), ash content (ASH), and fixed carbon content (FIX) in accordance with the ASTM D3172-89. Equations are presented below:

$$MC\ (\%): \frac{w-x}{w} \times 100\% \quad (1)$$

Where: MC – moisture content (%); w – air-dried mass (g); x – mass after dried at 105°C (g).

$$VMC\ (\%): \frac{x-y}{x} \times 100\% \quad (2)$$

Where: VMC – volatile matter content (%); y – mass after heated in a furnace at 950°C (g).

$$ASH\ (\%): \frac{z}{x} \times 100\% \quad (3)$$

Where: ASH – ash content (%); y – mass after heated in a furnace at 750°C (g).

$$FIX\ (\%): 100\% - (MC(\%) + VMC(\%) + ASH(\%)) \quad (4)$$

Where: FIX – fix carbon content

Calorific value characterization of TMWP

The calorific value (CAL) was determined by using an IKA C-200 bomb calorimeter based on ASTM-D5865-10a.

Experimental design

In order to determine the impact of torrefaction on the quality of the pellets, an analysis of variance (ANOVA) was performed using the SPSS program (version 20 IBM, New York USA), with significance differences set at 95%. Factors that were found to have a significant effect on pellet quality were subjected to a Tukey Honestly Significant Difference (HSD) analysis, which enabled the identification of genuine differences between the various torrefaction variations.

Results and Discussion

TMWP yield and appearance

Table 1 shows that the yield of merbau wood pellet torrefaction was obtained at 82.70–87.90%. The highest yield was produced by merbau wood pellet torrefaction at a temperature of 250°C for 15 minutes, and the lowest yield by torrefaction with a temperature of 250°C for 30 minutes.

It could be seen in *Fig. 1* that slight deformation occurred after torrefaction was implied to merbau wood pellets. Slight color and shape change of merbau wood pellets occurred. The color slightly changed to a darker brown, shape slightly bent, and little voids appeared.

Fig. 1. *Merbau pellets without torrefaction (a); torrefied merbau pellets (b)*

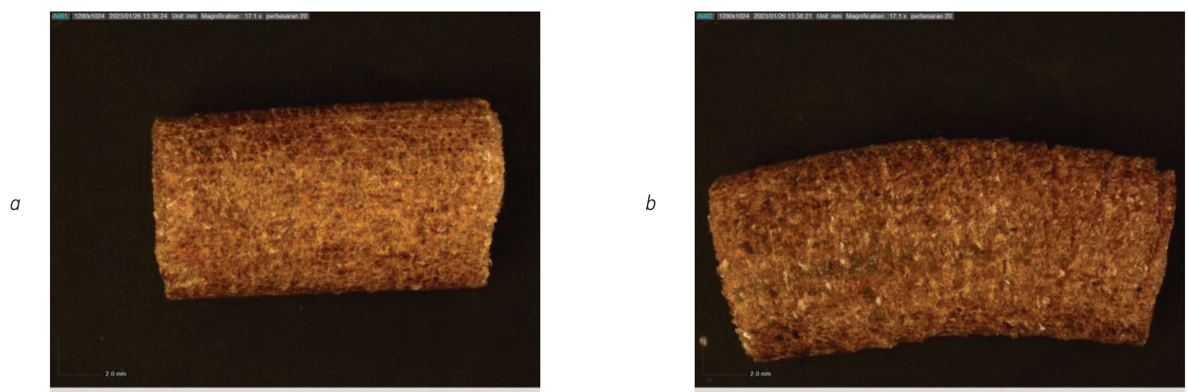


Table 1. *The characteristics of different types of TMWP*

Parameters	Types of pellets					DIN EN 15270
	Non-torrefied merbau wood pellets*	Torrefied 200°C/15 minutes	Torrefied 200°C/30 minutes	Torrefied 250°C/15 minutes	Torrefied 250°C/30 minutes	
Torrefaction Yield (%)	-	87.56 ± 0.54	87.18 ± 0.87	87.90 ± 0.93	82.70 ± 1.08	
COM (N)	598.06 ± 53.38*	254.52 ± 25.03	242.62 ± 24.16	237.89 ± 22.91	234.70 ± 12.86	
MC (%)	10.70 ± 0.29*	1.51 ± 0.11	0.23 ± 0.00	0.77 ± 0.06	1.68 ± 0.13	< 10
VMC (%)	80.29 ± 0.25*	79.91 ± 0.52	78.68 ± 1.65	76.57 ± 1.10	74.72 ± 1.93	
ASH (%)	1.82 ± 0.04*	1.80 ± 0.14	1.81 ± 0.14	1.84 ± 0.14	1.82 ± 0.14	< 0.5
FIX (%)	7.19 ± 0.48*	16.93 ± 0.43	19.29 ± 1.66	20.85 ± 1.67	22.17 ± 1.90	
CAL (cal/g)	4761.8 ± 44.58*	4867.2 ± 33.46	4893.4 ± 7.96	4893.6 ± 108.94	5093.6 ± 135.30	> 4302

Note: The average of 5 pellets repetition ± the standard deviation; data source Prasetyadi and Sutapa (2023)*

Table 2. *ANOVA analysis result of torrefied merbau wood pellets*

Source of variation	df	COM	MC	VMC	ASH	FIX	CAL
Torrefaction temperature (T)	1	ns	*	*	ns	*	*
Torrefaction duration (D)	1	ns	*	*	ns	*	**
TxD	1	ns	*	ns	ns	ns	**
Error	20						
Total	23						

*Note: df – degree of freedom; *P < 0.01; **P < 0.05; ns – nonsignificant*

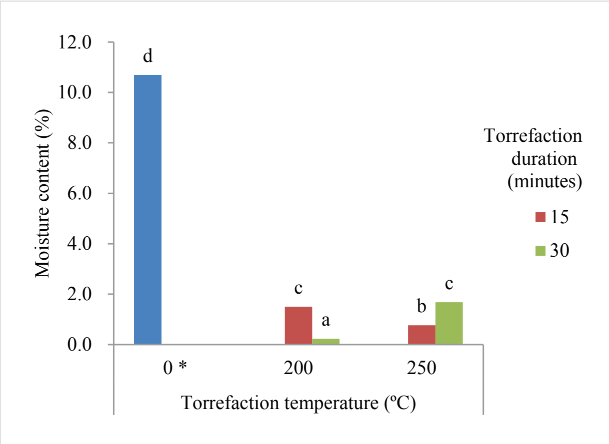
Torrefied merbau pellets mechanical properties

Larsson and Samuelsson (2017) indicated that compressive strength has a strong correlation with pellets durability. Thus, it was possible to portray compressive strength as pellets durability. *Table 1* shows that there is a decrease in the compressive strength of merbau wood pellets after torrefaction treatment. However, the decrease was not significant as proven by the ANOVA results which can be seen in *Table 2*, where all factors did not have a significant effect on the compressive strength of the pellets at any *P* value. A decrease in the mechanical properties of torrefied pellets can also be found in other studies such as Wang et al.'s (2020) where there was a decrease in tensile strength in torrefaction of spruce stem wood, bark, and forest residues pellets as the temperature and duration of torrefaction increased. This occurs due to the fact that as the torrefaction temperature increases, cellulose and lignin begin to decompose and form micropores; therefore, the pellet density decreases and the mechanical strength decreases (Zhang et al., 2020). However, since the decrease in compressive strength of TMWP was statistically insignificant, the performed torrefaction resulted in merbau pellets with the compressive strength that was not much different from merbau pellets without torrefaction.

Torrefied merbau pellets proximate properties

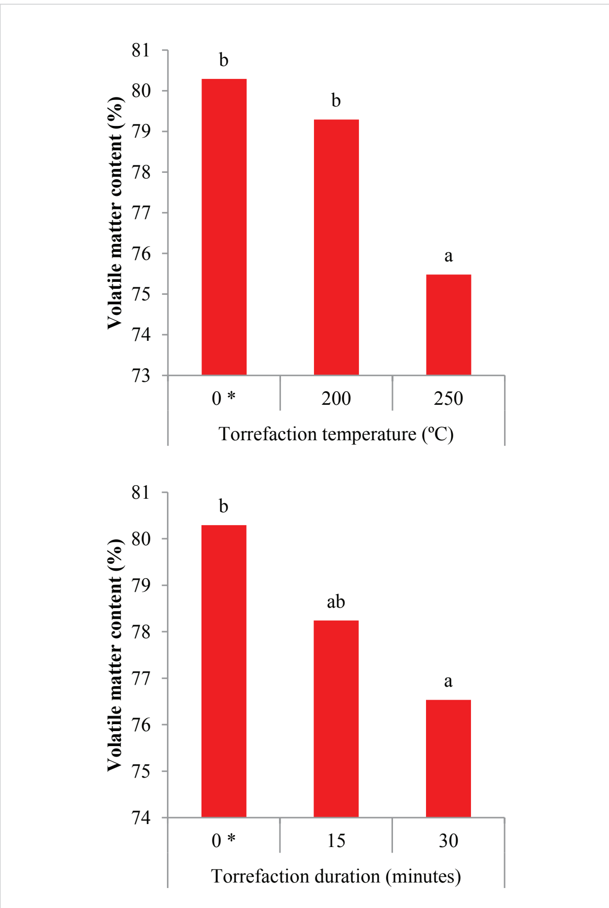
Table 1 shows that merbau wood pellet torrefaction produced proximate properties of MC, VMC, ASH, and FIX ranging within 0.23%–1.68%, 74.72%–79.91%, 1.80%–1.84%, and 16.93%–22.17%, respectively. The lowest value of moisture content was obtained in the torrefaction of merbau wood pellets with a temperature of 200°C with a duration of 30 minutes (0.23%), and the lowest volatile matter content was obtained in

Fig. 2. *Effects of torrefaction on pellets moisture content*



**data source Prasetyadi and Sutapa (2023); different letters represent a significant difference, P < 0.01*

Fig. 3. *Effects of torrefaction temperature on pellets volatile matter content*



**data source Prasetyadi and Sutapa (2023); different letters represent a significant difference, P < 0.01*

the torrefaction with a temperature of 250°C with a duration of 30 minutes (74.72%), the lowest ash content (1.80%) was obtained in the torrefaction of pellets with a temperature of 200°C with a duration of 15 minutes (16.93%–22.17%), and the highest bound carbon content was obtained in the torrefaction of pellets with a temperature of 250°C with a duration of 30 minutes (22.17%). The quality improvement obtained from the torrefaction treatment on the proximate properties of merbau wood pellets was apparent as the moisture content decreased by 98%, volatile matter content decreased by 7%, ash content decreased by 1%, and fixed carbon content increased by 208%.

The ANOVA test results in *Table 2* show a significant effect by the interaction factor of torrefaction temperature and duration on the moisture content of merbau wood pellets. The difference between interactions can be seen in *Fig. 2* where a significant decrease in moisture content can be seen in any torrefaction temperature or duration. A significant decrease can be found in the torrefaction at a temperature of 200°C from 15 minutes to 30 minutes. However, in comparison with the TMWP at a temperature of 200°C for 30 minutes, torrefaction at a temperature of 250°C for both 15 and 30 minutes showed a significant increase (*Fig. 2*).

The volatile matter content of merbau wood pellets decreased significantly from each factor of torrefaction temperature and duration (*Table 2*). The temperature factor showed that the significant decrease was apparent at the temperature of 250°C, while the duration factor showed a significant decrease at a torrefaction duration of 30 minutes (*Fig. 3*). Thus, as for the volatile matter content of TMWP, it started decreasing significantly when torrefied at a temperature of 250°C or torrefied for 30 minutes.

The ash content of merbau wood pellets did not change significantly after torrefaction as seen from the ANOVA test results (*Table 2*). Fixed carbon content increased significantly from each factor of the torrefaction temperature and duration (*Table 2*). The temperature factor showed that torrefaction at 200°C increased significantly, and a significant increase of fixed carbon content was also apparent after increasing the temperature at 250°C. Meanwhile, the duration factor fixed carbon content of TMWP significantly increased at 15 minutes torrefaction duration, and also increased after the torrefaction duration was extended to 30 minutes (*Fig. 4*).

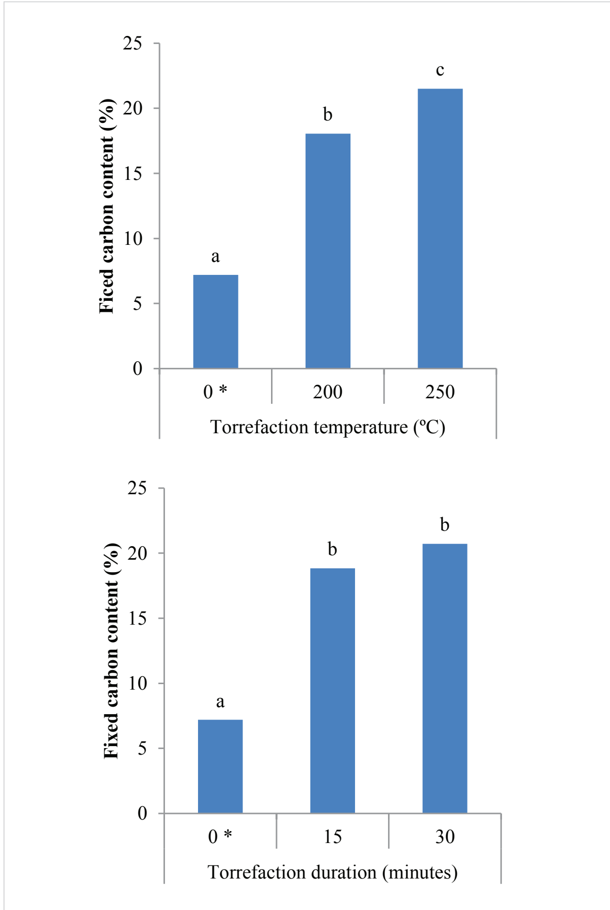
Similar results were also shown by Peng et al. (2013) where there was a decrease in the moisture content and volatile matter content, as well as an increase in fixed carbon content in pine sawdust pellets after torrefaction at 280°C with a duration of 52 minutes and at 300°C with a duration of 15 minutes. The low moisture content of wood pellets after torrefaction gives the advantage of being resistant to storage for a longer period when compared to regular pellets or wood chips (Nunes et al., 2014). Moreover, with the decrease in the volatile substance content of the pellets, the fixed carbon content increases, so the calorific value will also increase because fixed carbon has a role as the main fuel for biofuel (Sukarta et al., 2018).

Torrefied merbau pellets calorific value

Table 1 displays the calorific value range (4867.2–5093.6 cal/g) of merbau wood pellets after torrefaction. The highest calorific value was obtained in the torrefaction of pellets with a temperature of 250°C with a duration of 30 minutes. The increase obtained from the torrefaction treatment was 7% of the calorific value of merbau wood pellets without torrefaction treatment. *Table 2* shows that the interaction of the two factors, namely torrefaction temperature and torefaction duration, had a significant effect on the calorific value of merbau wood pellets. The honestly significant difference between factor interactions can be seen in *Fig. 5* where the increase in calorific value of merbau wood pellets experienced a significant increase in torrefaction with a temperature of 250°C and a duration of 30 minutes. Torrefaction with a temperature of 200°C both for 15 and 30 minutes and for 250°C for 15 minutes did not show any significant increase on TMWP calorific value, shown by the same letter represented after the HSD test (*Fig. 5*).

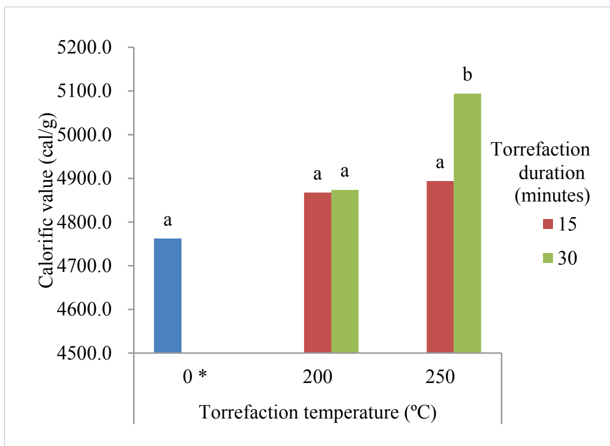
The increase in calorific value is one of the main objectives of torrefaction. The result shows a similarity with other studies. For example, the torrefaction of agro-pellets at a temperature of 210–250°C for 50 minutes increases the higher heating value from 4110 cal/g to 6880 cal/g and changes the lower heating value from 3780 cal/g to 6520 cal/g (Park et al., 2020). Other reports such as Garcia et al.'s (2018) also showed an increase of 11.1% in its calorific value for torrefied pine pellets. An increase in heating value occurs because, in the torrefaction process, biomass loses more oxygen and hydrogen than carbon (Uslu et al., 2008).

Fig. 4. *Effects of torrefaction duration on pellets fixed carbon content*



**data source Prasetyadi and Sutapa (2023); different letters represent a significant difference, P < 0.01*

Fig. 5. *Effects of torrefaction on pellets calorific value*



**data source Prasetyadi and Sutapa (2023); different letters represent a significant difference, P < 0.01*

Conclusions

From this study, it could be concluded that after the torrefaction treatment on merbau wood pellets, appearance and quality improvement were apparent. Torrefaction yield was obtained within 82.70%–87.90%. Slight color change to a darker brown, slightly bent shape, and little voids were also apparent. TMWP compressive strength decreased, although insignificantly. Furthermore, moisture content and volatile matter content significantly decreased as the temperature and duration of torrefaction increased. Ash content was not affected by the torrefaction treatment. Finally, fixed carbon content significantly increased as the temperature and duration of torrefaction increased, resulting in a significantly higher calorific value. Hence, this indicates that applying torrefaction on merbau wood waste pellets is a fulfilled alternative method to produce high quality pellets.

Acknowledgements

The Laboratory of Bioenergy and Biomaterial Conversion at the Faculty of Forestry, Universitas Gadjah Mada, Yogyakarta, Indonesia helped with this study. Additionally, the authors would like to express their gratitude to CV. Indo Jati Utama for providing the merbau wood waste used in this research.

References

ASTM D 3172-89 (2002) Standard Practice for Proximate Analysis of Coal and Coke, ASTM International, West Conshohocken, PA. Available at: https://webstore.ansi.org/standards/astm/astmd3172892002

ASTM D 5865-10a (2010) Standard Test Method for Gross Calorific Value of Coal and Coke, ASTM International, West Conshohocken, PA. Available at: https://www.astm.org/d5865-10a.html

ASTM D 4179-01 (2011) Standard Test Method for Single Pellet Crush Strength of Formed Catalysts Shapes, ASTM International, West Conshohocken, PA. Available at: https://webstore.ansi.org/standards/astm/astmd417901

Bergman P.C., Kiel J.H. (2005) Torrefaction for biomass upgrading. 14th European Biomass Conference & Exhibition Paris, France, 17-21 October 2005, pp 17-21. Available at: https://www.researchgate.net/profile/J-Kiel/publication/228699171_Torrefaction_for_biomass_upgrading/links/00b4952a70f4d9a5b9000000/Torrefaction-for-biomass-upgrading.pdf

Betahita. (2022) Memantau ke Mana Merbau Merantau [Monitoring Where Merbau Migrates]. Available at: https://betahita.id/news/detail/7138/memantau-ke-mana-merbau-merantau.html (accessed 10 May 2023) (in Indonesian)

Chen W.H., Lin B.J., Lin Y.Y., at al. (2021) Progress in biomass torrefaction: Principles, applications and challenges. Progress in Energy and Combustion Science 82: 100887. https://doi.org/10.1016/j.pecs.2020.100887

Craven J.M., Swithenbank J., Sharifi V.N., Peralta-Solorio D., Kelsall G., and Sage P. (2015) Hydrophobic coatings for moisture stable wood pellets. Biomass and Bioenergy 80: 278-285. https://doi.org/10.1016/j.biombioe.2015.06.004

DIN EN 15270 (2007) Pellet Burners for Small Heating Boilers. Definitions, Requirements, Testing, Marking, Deutsches Institut für Normung, Berlin, Germany. Available at: https://www.en-standard.eu/din-en-15270-pellet-burners-for-small-heating-boilers-definitions-requirements-testing-marking/

Chandel R., Kumar S. and Kumar R. (2016) Performance and emission characteristics in a diesel engine using cotton seed oil and diesel blend. Int J Enhanced Res Sci Technol Eng, 5: 78-84. https://www.erpublications.com/uploaded_files/download/download_27_02_2016_15_36_11.pdf

Forero Núñez C.A., Jochum J., and Sierra Vargas F.E. (2012) Characterization and feasibility of biomass fuel pellets made of Colombian timber, coconut and oil palm residues regarding European standards. Environmental biotechnology 8. bwmeta1.element.baztech-65936271-8bea-45b3-834f-c8df0d23377e

Garcia D.P., Caraschi J.C., Ventorim G., Vieira F.H.A., and de Paula Protásio T. (2018) Comparative energy properties of torrefied pellets in relation to pine and elephant grass pellets. BioResources 13(2): 2898-2906. https://doi.org/10.15376/biores.13.2.2898-2906

Goga, G., Afridi, M.S., Mewada, C., Prasad, J., Mohan, R., Yadav, A.S., Chakroborty, S. and Kumar, S. (2023) Heat transfer enhancement in solar pond using nano fluids. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2022.12.238

Guo M., Song W., and Buhain J. (2015) Bioenergy and biofuels: History, status, and perspective. Renewable and sustainable energy reviews 42: 712-725. https://doi.org/10.1016/j.rser.2014.10.013

Gupta V., Kumar S. and Kumar, R. (2020) Biodiesel as an alternate energy resource: a study. Asian Rev Mech Eng 9: 50-58. https://doi.org/10.51983/arme-2020.9.1.2470

Holm J.K., Henriksen U.B., Hustad J.E. and Sørensen L.H. (2006) Toward an understanding of controlling parameters in softwood and hardwood pellets production. Energy & Fuels 20(6): 2686-2694. https://doi.org/10.1021/ef0503360

Kumar L., Koukoulas A.A., Mani,S. and Satyavolu J. (2017) Integrating torrefaction in the wood pellet industry: A critical review. Energy & Fuels 31(1): 37-54. https://doi.org/10.1021/acs.energyfuels.6b02803

Kumar R., Kumar M., Chohan J.S. and Kumar S. (2022) Overview on metamaterial: History, types and applications. Materials Today: Proceedings 56: 3016-3024. https://doi.org/10.1016/j.matpr.2021.11.423

Larsson S.H., Samuelsson R. (2017) Prediction of ISO 17831-1: 2015 mechanical biofuel pellet durability from single pellet characterization. Fuel processing technology 163: 8-15. https://doi.org/10.1016/j.fuproc.2017.04.004

Mathews J.A. (2008). Carbon-negative biofuels. Energy policy 36(3): 940-945. https://doi.org/10.1016/j.enpol.2007.11.029

Nunes L.J.R., Matias J.C.O. and Catalão J.P.S. (2014) A review on torrefied biomass pellets as a sustainable alternative to coal in power generation. Renewable and Sustainable Energy Reviews 40: 153-160. https://doi.org/10.1016/j.rser.2014.07.181

Omer A.M. (2012) Biomass energy resources utilisation and waste management. Agricultural Sciences 3(1): 124-145. https://doi.org/10.4236/as.2012.31016

Owoyemi J.M., Zakariya H.O., Elegbede I.O. (2016) Sustainable wood waste management in Nigeria. Environmental & Socio-economic Studies 4(3): 1-9. https://doi.org/10.1515/environ-2016-0012

Park S., Kim S.J., Oh K.C., Cho L.H., Kim M.J., Jeong I.S., Lee C.G., Kim D.H. (2020) Characteristic analysis of torrefied pellets: Determining optimal torrefaction conditions for agri-byproduct. Energies 13(2): 423. https://doi.org/10.3390/en13020423

Peng, J.H., Bi, H.T., Lim, C.J., Sokhansanj, S. (2013) Study on density, hardness, and moisture uptake of torrefied wood pellets. Energy & Fuels 27(2): 967-974. https://doi.org/10.1021/ef301928q

Prasetyadi G.V., Sutapa J.P. (2023) Utilizing Merbau Wood and Coconut Shell Wastes as Biofuel in the Form of Pellets. Journal of Ecological Engineering 24(1): 172-178. https://doi.org/10.12911/22998993/156057

Procha A., Kumar R., Kumar S., Sham R. and Brar A.S. (2019) Biodiesel production from palm methyl ester (PME)-review. Int J Sci Manage Stud 2: 64-71. https://doi.org/10.51386/25815946/ijsms-v2i1p108

Sukarta I.N., Sastrawidana I.D.K., Ayuni N.P.S. (2018) Proximate analysis and calorific value of pellets in biosolid combined with wood waste biomass. Journal of Ecological Engineering 19(3). https://doi.org/10.12911/22998993/86153

Tumuluru J., Sokhansanj S., Hess J.R., Wright C.T., Boardman R.D. (2011) A review on biomass torrefaction process and product properties for energy applications. Industrial Biotechnology 7(5): 384-401. https://doi.org/10.1089/ind.2011.7.384

Uslu A., Faaij A.P., Bergman P.C. (2008) Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy, 33(8), 1206-1223. https://doi.org/10.1016/j.energy.2008.03.007

Wang L., Riva L., Skreiberg Ø., Khalil R., Bartocci P., Yang Q., Yang H., Wang X., Chen D., Rudolfsson M., Nielsen H.K. (2020) Effect of torrefaction on properties of pellets produced from woody biomass. Energy & Fuels 34(12): 15343-15354. https://doi.org/10.1021/acs.energyfuels.0c02671

Zhang Y., Chen F., Chen D., Cen K., Zhang J., Cao X. (2020) Upgrading of biomass pellets by torrefaction and its influence on the hydrophobicity, mechanical property, and fuel quality. Biomass Conversion and Biorefinery: 1-10. https://doi.org/10.1007/s13399-020-00666-5