

Fuel Pellets from a Mixture of Rice Husk and Wood Particles

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The physical and mechanical properties were studied for fuel pellets made from a mixture of rice husk and *Gmelina arborea* wood particles. Pellet density, compressive strength, and abrasion resistance were used to evaluate pellet quality at various densification pressures and proportions of rice husk to wood particles. Pellet density and compressive strength increased from 850 to 1070 kg/m³ and 0.61 to 1.2 MPa, respectively, when densification pressure increased from 80 to 120 MPa. The abrasion resistance for all pellet samples in this study was < 2.0%. Proximate analyses of the fuel pellets showed that volatile matter, fixed carbon, and heating value were relatively high and increased with a higher proportion of wood particles. Ash levels were also high (1.3 to 17.8%), which could cause problems with emission and deposition during thermal conversion. In general, except for the ash content, the physical and mechanical properties of pellets made from rice husk and *G. arborea* wood particles in this study were within the acceptable limits to be used as fuel pellets for industrial heat applications.

Keywords: Pellets; Rice husk; *Gmelina arborea*; Biomass; Agricultural residue

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INTRODUCTION

The threat of climate change from the use of fossil fuels has resulted in worldwide interest in renewable energy for heat and electricity production (Heinimo and Junginger 2009). Biomass is widely available and can be used as a renewable energy source either by direct combustion to produce heat or by converting the material into various forms of biofuel (Saidur *et al.* 2010). Rice husk, the hard, outermost layer of rice grains that is separated during the milling process, is an abundant biomass that can be used to produce renewable energy. About 150 million tons of rice husks are generated annually in rice growing regions of South America, India, China, and Southeast Asia (Santiaguel 2013). It is considered a waste material and is often burned in fields or dumped in landfills or rivers, causing air and water pollution (Samson *et al.* 2000; Thao *et al.* 2011; Anshar *et al.* 2013). The open burning of rice husks results in the loss of energy equivalent to millions of barrels of oil to the atmosphere and in the emission of greenhouse gases and air pollution (CEC 2014). Although rice husks have been used to produce ceramics, silicon, fillers, compost, and catalysts, the low volume requirements of rice husks for these products have not significantly reduced the amount of rice husk waste each year (Rodrigues *et al.* 2010; Wang *et al.* 2011). Using rice husk as a feedstock to produce fuel pellets could potentially utilize a large volume of this biomass (Missagia *et al.* 2011). Fuel pellets are compressed solid fuel with high density and combustion efficiency used for industrial and residential heating applications (Oberberger and Thek 2004). The densification of biomass into pellets results

in a fuel source with high energy and bulk densities, reducing the costs of transportation, handling, and storage (Hartmann and Lenz 2012). Unfortunately, rice husk contains high levels of ash and alkali metals, which could lead to deposit formation during thermal conversion in boilers and furnaces (Mansaray and Ghaly 1997; Werther *et al.* 2000; Garivait *et al.* 2006; Rhen *et al.* 2007). These issues are common with agriculture-based feedstocks used for pellet production (Jenkins 1998). However, solutions to mitigate these challenges include efficient combustion technologies, feedstock pre-treatment, and utilizing additives to resolve ash-related problems (Funke and Ziegler 2010; Wang *et al.* 2012; James *et al.* 2012). An alternative method is to mix rice husks with woody biomass. Wood has inherently low levels of inorganic elements that could reduce the ash level of fuel pellets compared with pellets made from rice husk alone. In addition, the higher calorific value and lignin content of woody biomass could also improve rice husk fuel properties.

There are limited studies on combining rice husks with woody biomass to produce fuel pellets. The present study reports on the physico-mechanical properties of fuel pellets produced from a mixture of rice (*Oryza sativa* L.) husks and wood particles from *Gmelina arborea* Roxb. *G. arborea* residues (sawdust and shavings) are abundant in secondary wood processing plants in Southeast Asia and could potentially be used as a feedstock for pellet production.

EXPERIMENTAL

Rice Husks

Rice husks (50 kg) were collected from a local rice mill (Victoria, Laguna, Philippines) and transported to the laboratory. Samples of rice husks (500 g) were dried in a rotary drier set at 103 ± 2 °C for about 24 h to about 8% moisture content (dry basis). The dried rice husks were then hammermilled to pass through a 2-mm screen. The bulk density of the dried sample was determined using the ratio of the mass of tamped rice husk that occupied a 1000 mL glass cylinder. Particle size distribution was determined by passing a 100-g dry sample through US standard sieves, namely #10 (2 mm) and #18 (1 mm). After sieving, the mass retained on each sieve was weighed. Three replicate sieve measurements were used.

Wood Particles

A 10-year-old *G. arborea* tree (20 cm diameter, wood density 410 kg m^{-3}) was cut from a tree plantation at the University of the Philippines Los Banos in Mt. Makiling, Los Banos, Laguna. *G. arborea* is a fast-growing tree species widely cultivated in industrial tree plantations in the Philippines, Malaysia, Indonesia, and other Southeast Asian countries. Its wood is used for light construction, crafts, furniture, decorative veneers, pulp, fuel, and charcoal. A significant amount of *G. arborea* sawdust and shavings are widely available in secondary wood processing plants in the country. The log was transported to the laboratory, debarked, chipped, and hammermilled to about 2 mm particle size. The ground biomass was dried to 8% moisture content (dry basis). The bulk density and particle size distribution were determined as described above.

Pelletization

A single die pellet press with removable plunger, similar to that described by Rudolfsson *et al.* (2015), was used to produce pellets from a mixture of rice husk and *G. arborea* wood particles (Fig. 1). The die channel is 8.0 mm in diameter and 82 mm long with the end plugged by a removable backstop. The plunger consists of a 7.88 mm diameter iron rod connected to the crosshead of a 10 kN universal testing machine (AGS-X, Shimadzu, Kyoto, Japan). The die was lagged with a heating plate connected to a temperature controller and glass wool insulation. The temperature of the die was measured by a type K thermocouple embedded inside the wall of the die and connected to the temperature controller. For each trial, about 1.2 g of rice husk and wood particles was fed into the die channel and compressed at a rate of 5 mm minute⁻¹ until the target pressure was reached. The die was wiped clean using a paper towel and 80% ethanol before each use. The compression force and displacement during pellet formation were recorded using a personal computer running on Shimadzu Trapezium X version 1.4.2 software. To study the effects of process conditions on pellet quality, a completely randomized design with two factors was used. Treatments included various amounts of rice husk (0, 20, 40, 60, 80, and 100% by mass) and applied pressure (80, 100, and 120 MPa). The die temperature was kept at 100 °C as an initial trial indicated that pellet quality was best at this temperature. A one way analysis of variance (ANOVA) was performed using Statgraphics Centurion 16.1 software (2010) to determine whether the property tested was significant. The means were separated using Tukey's Honest Significant Difference (HSD) test ($\alpha = 0.05$). Twelve replicate pellets were made for each treatment condition.

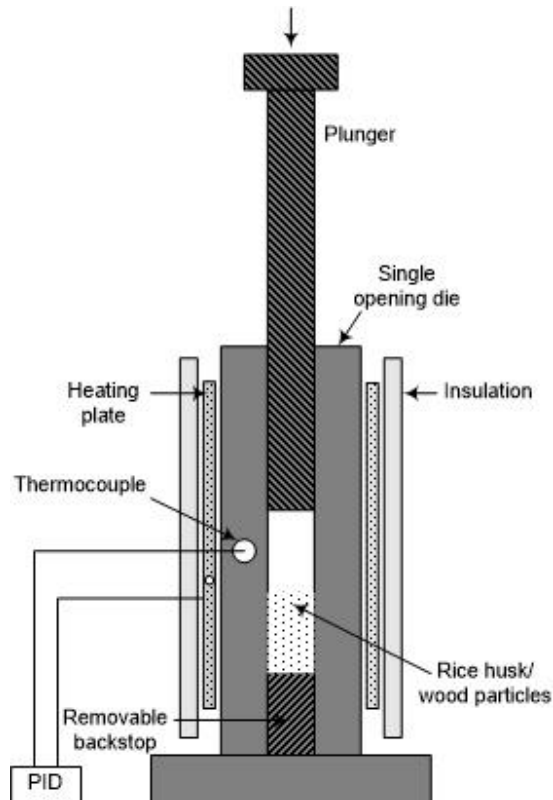


Fig. 1. Schematic diagram of a single die pellet press used to produce fuel pellets from mixture of rice husk and wood particles

Physical and Chemical Analysis

Pellets were randomly selected from each trial to measure physical and mechanical properties. Dimensions were determined by measuring the length and diameter of ten individual pellets. Pellet density was calculated based on the average weight and average volume of ten individual pellets. Four randomly selected pellets were ground and used for proximate analysis to determine moisture, ash content, and volatile matter using thermogravimetric-differential thermal analysis (TG-DTA, STA 6000, Perkin Elmer, Waltham, MA, USA). Gross calorific values (GCV) of pellets from each treatment combination were measured at constant volume on a dry basis using an isoperibol bomb calorimeter (Parr Instrument Company, St. Moline, IL, USA). Three replicates were used for each calorific measurement.

Mechanical Properties

All pellets were conditioned in a room at 23 °C and 65% relative humidity for two weeks prior to mechanical testing. Pellet compressive strength was determined by laying the pellet horizontally on a steel plate. A compression rod (8 mm diameter, 30 mm long) attached to the crosshead of the universal testing machine as described above was slowly moved downward to the center and perpendicular to the length of the pellet at a speed of 1 mm min⁻¹ until fracture was observed. The compressive strength of the pellet was determined as the maximum point of the force-displacement diagram as recorded by the Shimadzu data acquisition software described above. Three replicate pellets were tested for each treatment condition. The abrasion resistance was determined using a four-sided (12 cm × 30 cm) rotating chamber (15 rpm). Experimental pellets produced from a mixture of rice husk and wood particles were tumbled for 60 seconds to induce particle-to-particle collisions (EN 2009). After the tumbling period, the rice husk pellets were removed from the chamber and weighed; the difference between the total weight and weight after tumbling was determined (*i.e.*, weight of the fines). The abrasion resistance was expressed as the percentage of fine fractions of the total weight. Three replicate measurements were performed.

RESULTS AND DISCUSSION

Pellets formed from mixtures of rice husk and *G. arborea* wood particles were uniform in shape and diameter (8.4 to 8.5 mm) with some variation in length (17.3 to 22.6 mm). Bulk densities of the raw rice husk and wood particles were relatively low (Table 1) but within the range of acceptable values reported in the literature (Mansaray and Ghaly 1997; Acda and Devera 2014). Low bulk density of biomass materials results in poor mixing characteristics and non-uniform temperature distribution during thermal conversion processes (Lehtikangas 2001; Wu *et al.* 2011). Proximate analysis showed that pellets from all treatment combinations had less than 3% moisture after the pelleting process (Table 2). Volatile matter (65.2 to 79.3%) and fixed carbon (16.4 to 17.6%) were relatively high and increased with an increasing proportion of wood particles. The high amount of volatile matter and fixed carbon makes pellets from a mixture of rice husk and wood particles readily devolatilized when burned in boilers or furnaces. However, ash levels were relatively high (7.37 to 17.8%) compared to woody biomass at mixtures of 40 to 100% rice husk but decreased significantly (1.3 to 3.77%) with lower proportions of rice husks (20 to 40%). In contrast, pellets from woody biomass have generally low ash content (<1.0%)

and mixing it with rice husk would provide an opportunity to utilize this abundant agricultural residue. High amounts of ash in fuel pellets has a negative impact on their potential to be used as fuel for industrial or residential heating applications. Fuels with high ash contents are generally problematic during thermal conversion due to problems associated with ash removal, slagging, corrosion of equipment, and deposit formation in the furnace (Oberberger *et al.* 2006). However, equipment for continuous ash removal during combustion or the use of ash-mitigating additives has been used when rice husk is used as a fuel source (Werther *et al.* 2000; James *et al.* 2012; Wang *et al.* 2012). Heat values were relatively high, ranging from 17 to 18 MJ kg⁻¹ for pellets containing 20 to 60% rice husk, but decreased slightly to about 15 to 16 MJ kg⁻¹ at higher rice husk proportions (80 to 100%). Except for ash levels, the physical properties of pellets produced from a mixture of rice husk and wood particles as described above were within acceptable limits for industrial fuel pellets (ISO 2014).

Table 1. Particle Size Distribution and Bulk Density of Rice Husk and *G. arborea* Wood Particles

Material	Bulk Density (kg m ⁻³)	Particle Size (%)		
		> 2.0 mm	1.0-2.0 mm	< 1.0 mm
Rice husks	121.4 ± 3.23	2.46	41.27	56.25
Wood particles (<i>G. arborea</i>)	179.3 ± 1.46	80.69	14.38	4.93

Pellet density increased (850 to 1070 kg m⁻³) with increasing rice husk proportion by 8.2% to 17.6% (p-value < 0.05) using pressure levels from 80 to 120 MPa (Fig. 2). It is apparent that increasing the pressure consolidated more rice husk and wood biomass in the die channel, resulting in increased pellet density. Moreover, particle size distribution (Table 2) revealed that ground rice husk contains a high proportion of fine particles (56% < 1.0 mm). Fine particles can be easily compressed leading to a denser mass compared to larger and fibrous material during densification (Kaliyan and Morey 2009). A similar trend was reported in the densification of various biomasses into pellets or briquettes (Chin and Siddiqui 2000; Rhen *et al.* 2005; Gilbert *et al.* 2009). However, no significant increase (p-value < 0.05) in pellet density was observed with increasing pressure from 100 to 120 MPa at each proportion of rice husk investigated in this study (Fig. 2). The reason for this result is still unclear, but 100 MPa could be a limiting pressure for the consolidation of rice husk and woody biomass.

Table 2. Proximate Analyses of Pellets from Various Proportions of Rice Husk and *G. arborea* Wood Particles Formed at 100 MPa, 100 °C and 8% Moisture

Property (dry basis)	% Rice Husk					
	0	20	40	60	80	100
Moisture (%)	2.85	2.23	2.59	2.8	1.53	1.29
Ash (%)	1.41	3.77	7.37	10.41	13.9	17.8
Volatile matter (%)	79.32	77.16	74.99	70.71	68.27	65.26
Fixed carbon (%)	16.42	16.84	15.05	16.08	16.3	15.65
High heating value (MJ/kg)	18.85	18.72	17.75	17.23	16.1	15.2

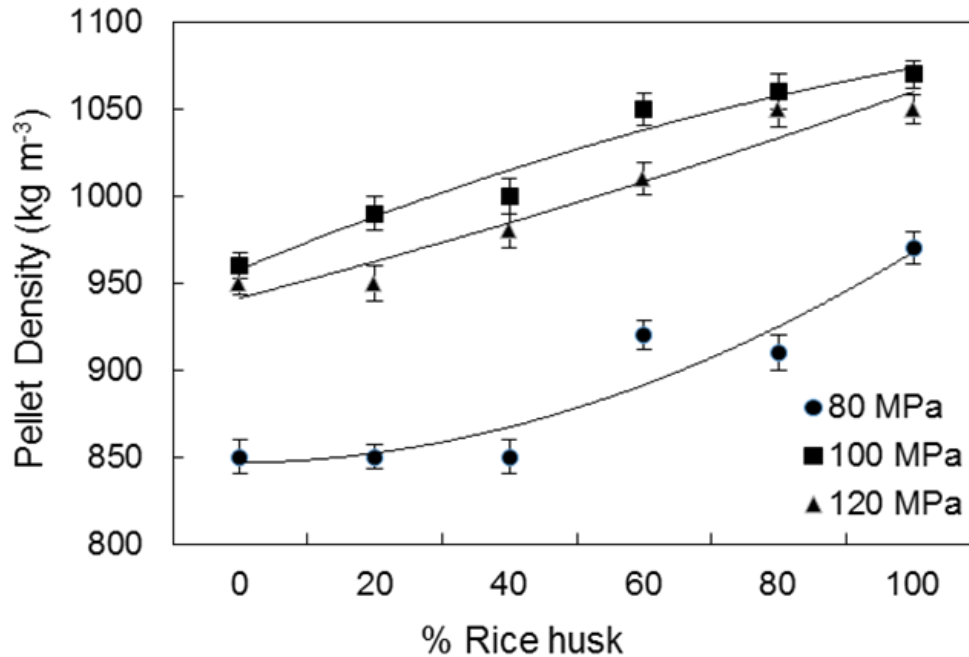


Fig. 2. Mean pellet density \pm standard error (SE) with varying amount of rice husk at increasing pressure from 80 to 120 MPa

The effect of pressure on pellet compressive strength with varying ratios of rice husk to wood particles is shown in Fig. 3. Pellet compressive strength increased by 6.5% to 31.6% (0.61 to 1.2 MPa) with increasing rice husk proportion and corresponding increase in pressure from 80 to 120 MPa. The significant increase (p -value < 0.05) in pellet compressive strength could be due to increased interfacial area and inter-diffusion of rice husk and wood particles at high consolidation pressure and temperature resulting in stronger van der Waals forces, hydrogen bonding, and mechanical interlocking between particles (Mani *et al.* 2006; Poddar *et al.* 2014). The significant amount of lignin in rice husk may have also contributed to the strength of the pellets (Gil *et al.* 2010). Lignin softens and helps the binding process during densification at high temperature and pressure (Kaliyan and Morey 2009).

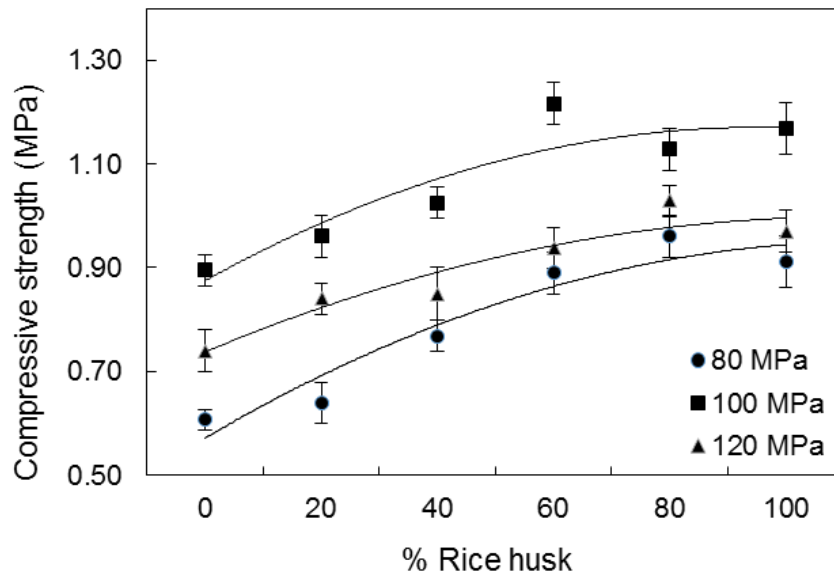


Fig. 3. Mean pellet compressive strength \pm SE at varying amount of rice husk at varying pressure from 80 to 120 MPa

Similar relationships between compressive strength and pressure for various biomasses have also been reported (Rhen *et al.* 2005; Poddar *et al.* 2014). Abrasion resistance was relatively low ($< 2.0\%$) for all pellet samples produced with treatment conditions and mixtures used in this study (Fig. 4); this is also within acceptable limits for use as industrial fuel pellets (ISO 2009). This indicates that pellets were well-formed and problems associated with high levels of fines, such as clogging and failures in storage and feeding systems, would be limited (Thomson and Liddell 2015). Low fines levels are also essential for convenience of end users to prevent dust emissions during combustion (Stahl and Wikstrom 2009).

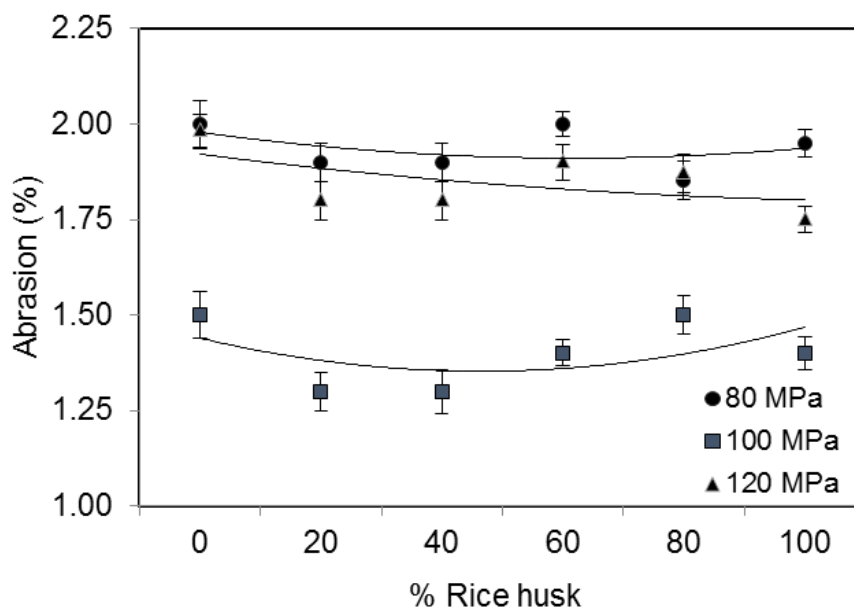


Fig. 4. Mean abrasion \pm SE at varying amount of rice husk at varying pressure from 80 to 120 MPa

CONCLUSIONS

1. The density and mechanical properties of pellets produced from mixtures of rice husk and *G. arborea* wood particles were influenced by densification pressure and the proportion of rice husk and wood particles. Pellet density and compressive strength increased with increasing pressure (80 to 120 MPa) and rice husk proportion. Abrasion resistance was low (< 2%) for all combinations of pressures and mixtures used in this study.
2. Proximate analyses showed that volatile matter and fixed carbon were relatively high, indicating good potential to be used as a solid fuel source for thermal conversion. However, ash levels were high (>10%) but decreased significantly with higher proportions of wood particles (*i.e.*, 20 to 40% rice husk).
3. Except for its high levels of ash compared with woody biomass, pellets produced from a mixture of rice husk and *G. arborea* wood particles have good potential to be used as compressed solid fuel for industrial heating applications, especially for furnace and boilers equip for ash removal. Further analysis and research is necessary to better understand the effect of process variables and feedstock characteristics on pellet quality.
4. The development fuel pellets from rice husk and wood particles could help reduce the amount of rice husk being burned in the field and help reduce emission of greenhouse gases that contribute to air pollution in many rice producing countries.

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REFERENCES CITED

- Acda, M. N., and Devera, E. E. (2014). "Physico-chemical properties of wood pellets from forest residues," *J. Trop. For. Sci.* 26(4), 589-595.
- Anshar, M., Abd Kader, A. S., and Ani, F. N. (2013). "The utilization potential of rice husk as an alternative energy source for power plants in Indonesia," *Adv. Mater. Res.* 845, 494-498. DOI: 10.4028/www.scientific.net/amr.845.494
- Commission for Environmental Cooperation (CEC) (2014). *Burning Agricultural Waste: A Source of Dioxins*, Montreal, Canada.
- Chin, O. C., and Siddiqui, K. M. (2000). "Characteristics of some biomass briquettes prepared under modest die pressures," *Biomass Bioenerg.* 18(3), 223-228. DOI 10.1016/S0961-9534(99)00084-7

- EN 15210-1 (2009). "Solid biofuels - Determination of mechanical durability of pellets and briquettes - Part 1: Pellets," European Committee for Standardization, Brussels, Belgium.
- Funke, A., and Ziegler, F. (2010). "Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering," *Biofuels, Bioprod, Biorefin.* 4(2), 160-177. DOI: 10.1002/bbb.198
- Garivait, S., Chaiyo, U., Putumsawad, S., and Deakhuntod, J. (2006). "Physical and chemical properties of Thai biomass fuel from agricultural residues," in: *The 2nd Joint International Conference on Sustainable Energy and Environment*, Bangkok, Thailand.
- Gil, M. V., Oulego, P., Casal, M. D., Pevida, C., Pis, J. J., and Rubiera, F. (2010). "Mechanical durability and combustion characteristics of pellets from biomass blends," *Bioresource Technol.* 101(22), 8859-8867. DOI: 10.1016/j.biortech.2010.06.062
- Gilbert, P., Ryu, C., Sharifi, V., and Swithenbank, J. (2009). "Effect of process parameters on pelletisation of herbaceous crops," *Fuel* 88(8), 1491-1497. DOI: 10.1016/j.fuel.2009.03.015
- Hartmann, H., and Lenz, V. (2012). "Biomass energy heat provision in modern small-scale systems," in: *Encyclopedia of Sustainability Science and Technology*, R. A. Myers (ed.), Springer, New York, NY.
- Heinimo, J., and Junginger, M. (2009). "Production and trading of biomass for energy - An overview of the global status," *Biomass Bioenerg.* 33(9), 1310-1320. DOI: 10.1016/j.biombioe.2009.05.017.
- ISO 17225-2 (2014). "Solid biofuels – Fuel specifications and classes – Part 2: Graded wood pellets," International Organization for Standardization, Geneva, Switzerland.
- James, A. K., Thring, R. W., Helle, S., and Ghuman, H. S. (2012). "Ash management review – Applications of biomass bottom ash," *Energies* 5(12), 3856-3873. DOI: 10.3390/en5103856
- Jenkins, B. M., Baxter, L. L., Miles, J. R., and Miles, T. R. (1998). "Combustion properties of biomass," *Fuel Proc. Technol.* 54(1-3), 17-46. DOI: 10.1016/S0140-6701(99)92787-X
- Kaliyan, N., and Morey, R. V. (2009). "Factors affecting strength and durability of densified biomass products," *Biomass Bioenerg.* 33(3), 337-359. DOI: 10.1016/j.biombioe.2008.08.005
- Lehtikangas, P. (2001). "Quality properties of pelletised sawdust, logging residues and bark," *Biomass Bioenerg.* 20(5), 351-360. doi.10.1016/S0961-9534(00)00092-1
- Mani, S., Tabil, L. G., and Sokhansanj, S. (2006). "Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses," *Biomass Bioenerg.* 30(7), 648-654. DOI: 10.1016/j.biombioe.2005.01.004
- Mansaray, K. G., and Ghaly, A. E. (1997). "Physical and thermochemical properties of rice husk," *Energ. Source* 19(9), 989-1004. DOI: 10.1080/00908319708908904
- Missagia, B., Guerrero, C., Narra, S., Sun, Y., Ay, P., and Krautz, H. J. (2011). "Physicomechanical properties of rice husk pellets for energy generation," *Energ. Fuel* 25(12), 5786-5790. DOI: 10.1021/ef201271b
- Obernberger, I., Brunner, T., and Barntaler, G. (2006). "Chemical properties of solid fuels – Significance and impact," *Biomass Bioenerg.* 30(11), 973-982. DOI: 10.1016/j.biombioe.2006.06.011

- Obernberger, T., and Thek, G. (2004). "Physical characterization and chemical composition of densified biomass fuels with regard to their combustion behavior," *Biomass Bioenerg.* 27(6), 653-669. DOI:10.1016/j.biombioe.2003.07.006.
- Poddar, S., Kamruzzaman, M., Sujana, S. M. A., Hossain, M., Jamal, M. S., Gafur, M. A., and Khanam, M. (2014). "Effect of compression pressure on lignocellulosic biomass pellet to improve fuel properties: Higher heating value," *Fuel* 131, 43-48. DOI: 10.1016/j.fuel.2014.04.061
- Rhen, C., Gref, R., Sjoström, M., and Wasterlund, I. (2005). "Effects of raw material moisture content, densification pressure and temperature on some properties of Norway spruce pellets," *Fuel Process Technol.* 87(1), 11-16.
- Rhen, C., Ohman, M., Gref, R., and Wasterlund, I. (2007). "Effect of raw material composition in woody biomass pellets on combustion characteristics," *Biomass Bioenerg.* 3(1), 66-72. DOI: 10.1016/j.biombioe.2006.06.016
- Rodrigues, C. D. S., Ghavami, K., and Stroeven, P. (2010). "Rice husk ash as a supplementary raw material for the production of cellulose-cement composites with improved performance," *Waste Biomass Valor.* 1(2), 241-249. DOI: 10.1007/s12649-010-9017-7
- Rudolfsson, M., Stelte, W., and Lestander, T.A. (2015). "Process optimization of combined biomass torrefaction and palletization for fuel pellet production – A parametric study," *Appl. Energ.* 140, 378-384. DOI: 10.1016/j.apenergy.2014.11.041
- Saidur, A., Abdelaziz, E., Demirbas, A., Hossain, M., and Mekhilef, S. (2010). "A review on biomass as a fuel for boilers," *Renew. Sustain. Energy Rev.* 15(5), 2262-2289. DOI: 10.1016/j.rser.2011.02.015
- Samson, R., Helwig, T., Stohl, D., De Maio, A., Duxbury, P., Mendoza, T., and Elepano, A. (2000). *Strategies for Enhancing Biomass Energy Utilization in the Philippines*, National Renewable Energy Laboratory, Golden, CO, USA.
- Santiaguel, A. F. (2013). "A second life for rice husk," *Rice Today* April-June, 12-13.
- Stahl, M., and Wikström, F. (2009). "Swedish perspective on wood fuel pellets for household heating: A modified standard for pellets could reduce end-user problems," *Biomass Bioenerg.* 33(5), 803-809. DOI: 10.1016/j.biombioe.2008.12.003
- Statgraphics Centurion XVI (2010). *User's Manual*, Manugistics Inc., Rockville, MD, USA.
- Thao, P. T. M., Kurisu, K. H., and Hanaki, K. (2011). "Greenhouse gas emission mitigation potential of rice husks for An Giang province, Vietnam," *Biomass Bioenerg.* 35(8), 3656-3666. DOI: 10.1016/j.biombioe.2011.05.023
- Thomson, H., and Liddell, C. (2015). "The suitability of wood pellet heating for domestic households: A review of literature," *Renew. Sustain. Energy Rev.* 42, 1362-1369. DOI: 10.1016/j.rser.2014.11.009
- Wang, L., Hustada, J. E., Skreiberg, O., Skjevraka, G., and Gronli, M. (2012). "A critical review on additives to reduce ash related operation problems in biomass combustion applications," *Energy Procedia* 20, 20-29. DOI: 10.1016/j.egypro.2012.03.004
- Wang, W., Martin, J. C., Zhang, N., Ma, C., Han, A., and Sun, L. (2011). "Harvesting silica nanoparticles from rice husks," *J. Nanopart. Res.* 13(12), 6981-6990.
- Werther, J., Saenger, M., Hartge, E. U., Ogada, T., and Siagi, Z. (2000). "Combustion of agricultural residues," *Prog. Energ. Combust.* 26(1), 1-27. DOI: 10.1007/s11051-011-0609-3

Wu, M. R., Schott, D. L., and Lodewijks, G. (2011) “Physical properties of solid biomass,” *Biomass Bioenerg.* 35(5), 2093-2105. DOI: 10.1016/j.biombioe.2011.02.020

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