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Effect of Particle Size on Mechanical Properties of Pellets Made from Biomass Blends

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Abstract

Woody biomass is densified in the form of pellets in order to improve its physical and mechanical properties during handling and storage. However, limited research work has been conducted on the mechanical properties of pellets made from agricultural and wood biomass blends. Two commonly available forestry biomass, spruce (S) and pine (P), and three agricultural biomasses, reed canary grass (RCG), timothy hay (H) and switchgrass (SW), were used to form pellets. The mechanical properties were evaluated for three different particle sizes (150-300, 300-425 and 425-600 µm). An Instron attached with an in-house built single unit pelletizer and temperature controlled die was employed to produce a pellet. The aim of this study is to investigate the effect of particle size and blending (agricultural and woody biomass) on the mechanical properties (density and intrinsic yield stress). For all biomasses, pellets made from lower particle size (150-300 µm) exhibited higher density (950-1178 kg/m^3 for spruce and pine; 668-800 kg/m^3 for RCG, H and SW; 900-970 kg/m^3 for blended biomass). The intrinsic yield stress exhibited differences in values for individual forestry (40 MPa) and agricultural biomass (27-48 MPa), however after blending the values converged closest to that value for forestry biomass. In conclusion, blending low cost and abundant available agricultural biomass with woody biomass could not only result in better mechanical properties but would also help to meet the pellet market demand in future.

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Keywords: agricultural biomass; biomass pellets; axial stress; blended biomass; pellet's density

1. Introduction

Biomass densification provides better physical and combustion properties for pellet fuel industries [1]. It has drawn world attention due to its advantaged over wide range of raw biomass which includes agricultural and forestry residues as energy sources [2]. Production of pellets and its demand have been rapidly increased in Canada, America, Europe, and China in the past few years. It is estimated that the demand for pellets will be triples from 2012 to 2020, rising from 16 million to 46 million metric tons per year [3]. As one of the main pellets produces, the Canadian pellet industry is looking for alternative sources of feedstock. Agricultural residues can be one of the potential alternative feedstock since it is abundantly available of about 25 Mtoe (Megatonne of oil equivalent), annually [4, 5] and at low cost. Based on physical and mechanical characteristics, biomass pellets have been presented to significantly reduce costs of storage and transportation [6].

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Several studies have been reported on pelleting, focusing on material and process parameters and bonding formation [7, 8, 9, and 15]. Both temperature and applied pressure were found to be the influential parameters in determining the quality of pellets. Material characteristics of different biomasses have also been explored for its relationship with particle bonding in pellets made from beech, fir and straw [10]. They analyzed the fracture surface of the pellet and it was found that pellets made from beech and fir had a greater mechanical resistance than pellets made from straw. It is also concluded that pellets made at temperature 100 °C had greater influence on mechanical stability than pellets made at temperature 20 °C. The published work related to biomass pelleting, has also been focused on economic analysis [6, 11, and 12]. Very limited research work has been reported in the open literature about producing pellet by method of blending agricultural biomass with woody biomass, it is hypothesized that blending agricultural biomass in current woody biomass based pellets might give direction in the development of new feedstock. The purpose of this work is to investigate the effect of particle size on density and yield stress of pellets made from selected individual agricultural and woody biomasses and their blends.

2. Methodology

2.1. Sample preparation

In this study, the selected agricultural biomass such as reed canary grass, timothy hay and switchgrass was provided by New Brunswick Department of Agriculture. The woody biomass (spruce and pine) was obtained from a local saw mill situated in New Brunswick. The raw biomass materials placed in plastic bags and in closed container were stored at room conditions. Prior to analysis, the samples were dried in the oven at 105 °C for 24 h, and then ground using Wiley mill to less than 1 mm particle size. The ground biomass were sieved according to ASTM standards (D 2013-72) to collect the particle size in range of 150-300, 300-425 and 425-600 μm. The grinded biomass and their blends were stored in airtight container prior to pelletizing and for further analysis. Heating value, proximate, and ultimate analysis was conducted for individual and blended biomass and is presented in Table 1.

Table 1. Biomass and blending ratio.

	Agricultural			Forestry		Blends					
	RCG	H	SW	S	P	S+RCG	P+RCG	S+H	P+H	S+SW	P+SW
Proportion (wt. %)	100	100	100	100	100	50:50	50:50	50:50	50:50	50:50	50:50

Notes: RCG=Reed Canary grass, H=Timothy hay, SW=Switchgrass, S=Spruce and P=Pine

2.2. Proximate and ultimate analysis

The ultimate analysis was performed using LECO CHNS 932 elemental analyzer as per the ASTM D5291 method and was repeated twice. Element oxygen was calculated by difference. Proximate analysis was determined twice using TG analyzer (Q500 TA Instrument Inc.) as per ASTM E1641-04 method, while the ash content was investigated as per NREL/TP-510-42622 method with 6 replications. The higher heating value (HHV) of a biomass was measured using a bomb calorimeter (Isoperibol Oxygen Bomb Calorimeter) according to the standard method, ASTM D-5865.

2.3. Pelletization process

Prior to palletization the ground biomass that was stored in an airtight container was maintained under room condition for about a week. The pellets were formed with the adjusted moisture content of about 10 %. Pellets were made with the help of a closed end die which was built in house. The close end die with 8 mm diameter and 202 mm in length as shown in Figure 1 was attached to Instron SATEC Compression Machine which had a control on the load and holding time. The temperature was controlled by the help of K-type thermocouples connected to a PID controller.

The selection of pressure, temperature, speed of the piston and holding time for this work were based on the previous detailed studies [13, 15]. They found highest durability of pellets made from switchgrass and spruce in the temperature range between 80-85 °C. A total number of 330 (11 types of biomass × 3 particle sizes × 10 replications) experimental tests were performed based on number of biomass samples (5 individual and 6 blends), three different particle sizes and three replications. Approximately,

1.2 g of biomass sample was fed into die in each run to produce a single pellet. The energy required for densifying each biomass and blend biomass pellet was calculated using the plots of the force and displacement data recorded by the associated software of the Instron machine.

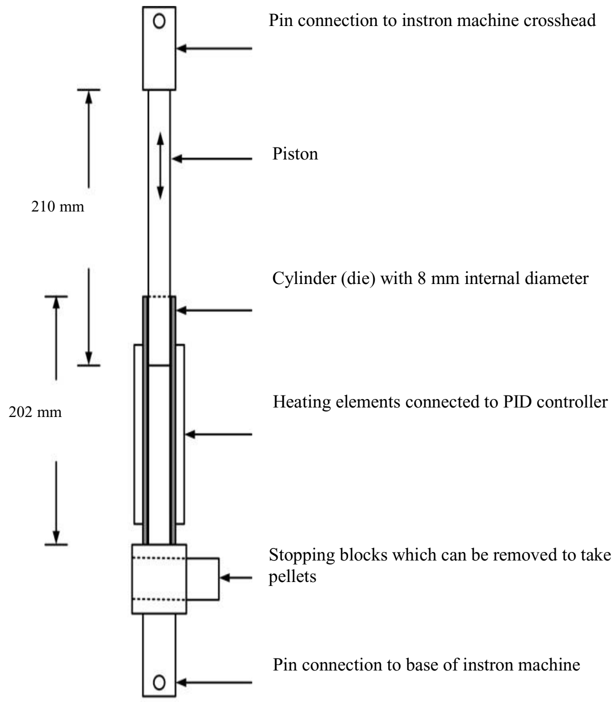


Figure 1. Schematic of single pelletization set up [13 and 14]

2.4. Density of pellets

Pellet size was measured with a digital caliper (0.01 mm resolution, model CD-56C, Mitutoyo Corp., Aurora, III.). Reported values are the average of 10 measurements for each biomass sample. True density of the pellets was calculated based on the ration of mass to the volume of single pellet.

2.5. Mechanical strength analysis

The mechanical strength of individual biomass and their blend pellets was measured using Instron SATEC Compression Machine. Each pellet was tested for each condition and was repeated thrice to present a mean value with the standard deviation.

3. Results and Discussion

3.1. Elemental analysis

Carbon, hydrogen and oxygen are the main biomass elements which directly presents the components of the organic part of fuel. Carbon is obviously representing foremost contributions to overall heating value. Generally, agricultural biomass has slightly lower (45 %) carbon content than woody (47 %) and blended biomass (46-47 %) as presented in Table 2. Harun and Afzal [14] have reported the same results of elemental analysis in the study. The biomasses as well as their blends chosen in this study have its benefits for combustion since almost half of it constituents were carbon. It mainly transforms to CO_2, released to atmosphere during combustion [16].

The carbon contents are also directly related to lignin, cellulose and hemicellulose contents in biomass. Lignin contributes to the mechanical properties of biomass pellets. Since agricultural biomass is difficult to pelletize, blending it with forestry biomass might improve the densification process due to more lignin content. Fuel rich in lignin has the total carbon and hydrogen content of higher than 50 % [17].

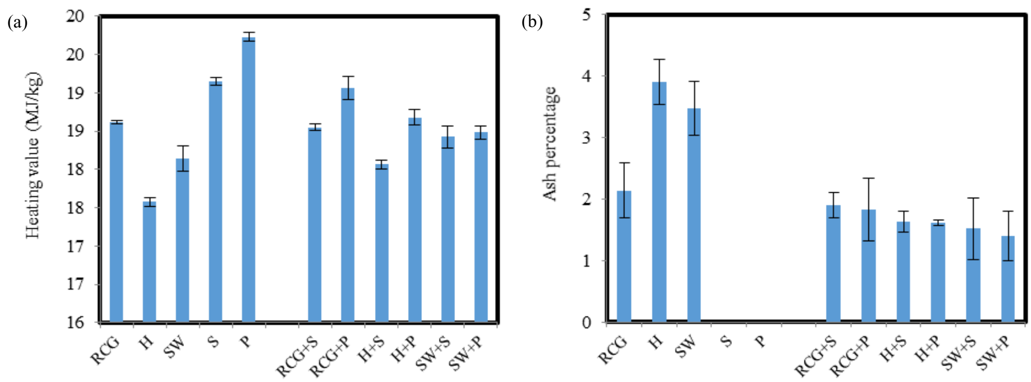
Table 2: Elemental analysis (dry basis) of individual and biomass blends

Biomass	C (wt % ± S.D)	H (wt % ± S.D)	N (wt % ± S.D)	S (wt % ± S.D)	O (balance) (wt % ± S.D)
Reed canary grass (RCG)	45.455±0.040	5.891±0.070	0.174±0.001	0.041±0.001	48.439±0.112
Timothy hay (H)	45.461±0.061	5.950±0.004	0.184±0.008	0.041±0.001	48.372±0.075
Switchgrass (SW)	45.033±0.003	5.981±0.001	0.119±0.001	0.028±0.001	48.840±0.020
Spruce (S)	47.142±0.043	6.060±0.044	0.040±0.001	0.002±0.000	46.760±0.087
Pine (P)	46.798±0.001	6.140±0.002	0.039±0.001	0.002±0.000	47.020±0.000
Blended biomass (50 wt %:50 wt %)					
RCG+S	46.645±0.019	6.068±0.016	0.035±0.001	0.016±0.001	47.135±0.037
RCG+P	45.983±0.000	6.022±0.001	0.036±0.001	0.017±0.001	46.912±0.022
H+S	46.568±0.004	6.012±0.001	0.040±0.001	0.018±0.001	47.358±0.006
H+P	46.720±0.006	6.081±0.003	0.038±0.002	0.017±0.001	47.140±0.013
SW+S	47.121±0.004	6.080±0.017	0.033±0.001	0.013±0.001	46.750±0.016
SW+P	47.208±0.002	6.120±0.001	0.027±0.001	0.010±0.001	46.644±0.010

Notes: C=carbon, H=hydrogen, N=nitrogen, S=sulfur, O=oxygen

3.2. Heating value and ash analysis

Biomass from agricultural and forest together with their blends were used in combustion tests in this study. Calorific values and ash analyses of the biomass fuels are given in Figure 2 (a) and (b), respectively. Analyses were performed according to ASTM standards. Forestry biomass is considered has higher lignin according to its carbon and hydrogen percentage, calculated on a dry, ash-free basis. The calorific values of spruce and pine were higher than the calorific values of reed canary grass, timothy hay and switchgrass, as presented in Figure 2 (a). Blended fuels have showed that the calorific values were mostly at the average values between their parent biomass. This can beneficial agricultural biomass as blending it with woody biomass can improve the heating value of agricultural biomass fuels.



Notes: RCG=reed canary grass, H=timothy hay, SW=switchgrass, S=spruce, P=pine

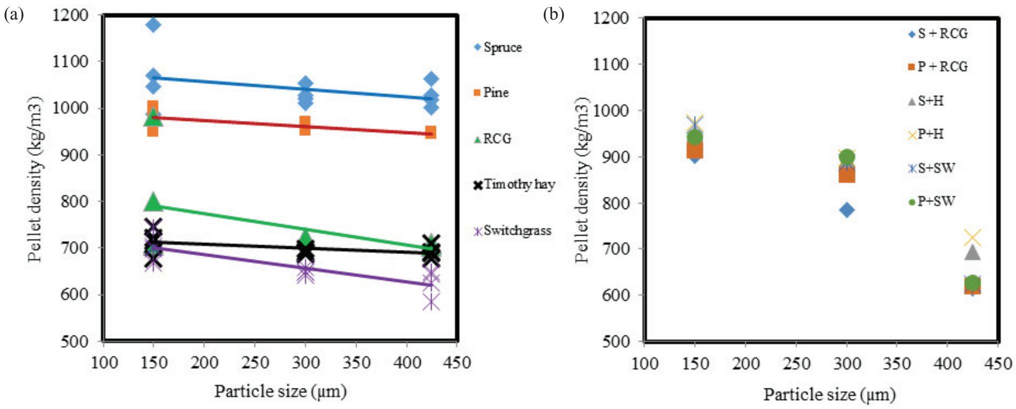
Figure 2. (a) Calorific values of agricultural, forestry biomass, and their blends; (b) Ash content of agricultural, forestry biomass, and their blends

Combustion of spruce and pine can be of less difficulty since its ash content was only found in traces (0.0004 mg). The average ash content of agricultural biomass, reed canary grass, timothy hay and switchgrass was obviously higher from 2 to 4 %, as presented in Figure 2 (b). High ash in agricultural biomass was due to high sulfur presented in the fuels as shown in Table 2. Blended samples were prepared by mixing agricultural and woody biomass in the proportion of 50:50 (agricultural wt%: woody wt%). The RCG blends was found still high in the ash content due to the high mineral contents in RCG [14]. The ash content was observed to be lesser than 2 %, which is highly recommended and above standard requirement according to national and international standard such as PFI (Pellet Fuel Institute).

3.3. Physical and mechanical behaviour

3.3.1. Effect of particle size on pellet density

The average diameter of these pellets was about 8.0 mm, and the average length ranged from 23 to 29 mm. Usually, the bulk density of the biomasses differ according to the particle size and moisture content [18 and 19]. However, the true density of biomass pellets is significantly higher than the original bulk density of biomass. For example, Colley et al. [20] reported that bulk density of ground switchgrass was 165.5 kg/m^3, but the density of pellets at 5% to 20% (wet basis) moisture content ranged from 536 to 708 kg/m^3. In the present study, the density of pellets made from spruce and pine ranged from 943 to 1178 kg/m^3. However, individual agricultural biomass showed lower pellet density ranging from 584 to 799 kg/m^3, as shown in Figure 3 (a).



Notation: RCG =Reed Canary grass, H=Timothy hay, SW=Switchgrass, S=Spruce, P=Pine

Figure 3. (a) Pellet density of individual agricultural and woody biomass at different particle sizes (150, 300 and 425 µm); (b) Density of biomass pellets made from blended biomass for particle size of 150, 300 and 425 µm

The density of blended biomass pellets increased significantly (627 to 969 kg/m^3) than the individual agricultural biomass pellets (Figure 3 (b)). Woody biomass particles might have played an important role in filling the void between the particles to increase the inter-particle bonding. The results from this study agreed well with the previous work as done by Arzola et al. [12]. They found that the density of oil palm shell pellets decreased as the average particle size was increased from 160 to 570 µm. Among the biomass studied, spruce pellets showed the highest density. Using the same amount of biomass (1.2 grams), the length of pellets made from agricultural biomass pellets which might have not easily filled while densifying. Morever, the inter-particle bonding in agricultural biomass is weaker [22 and 23] than the inter-particle bonding in woody biomass. The lignin content, determined by means of hydrolysis as per NREL 2008b standard, in spruce, pine, reed canary grass, timothy hay and switchgrass biomass was 23, 24, 17, 11 and 9 %, respectively. The density of biomass pellet varied according to the lignin content of biomass and it was low for low lignin content biomass. Therefore, there could be a strong relation between the density and the lignin content of the biomass.

3.3.2. Effect of particle size on pellet yield stress

Besides several other material and process parameters, particle size plays a major role in pellet quality and density. It significantly contributes to the mechanical strength of biomass pellets. During compaction, first layer of particles interacts with second layer of particles by pushing each other and filling the gaps. As other layers of particles keep moving and piled-up, particles resists each other and hence there is an increased inter-particle stress. A pellet made from smaller particle size gains higher strength due to decrease in gaps that have been filled by the smaller particles more than the pellet made from larger particle size. A change in particle size affects the yield strength of pellet due to the level of applied stress to cause the particle boundary to failure. Theories that have been proposed for the particle size dependence include the dislocation density model [24] and Hall-Petch equation, which has been widely applied for metals [25], nanocrystalline materials [26] and also biowaste eggshells [27]. It is difficult to develop an accurate model for the yield strength of the pellet, but it is found that the axial yield stress, σ_y, is related to particle diameter, d, of the selected biomass and their blends with the range of particle size used in this study and it behaved according to the *Hall-Petch equation*:

$$\sigma_y = \sigma_i + \frac{k}{\sqrt{d}}$$

where σ_i is the inherent compressive stress of biomass and k is a constant for a particular material. This relation is valid for particle size hardening at low temperature (< melting temperature, T_m). The effect of particle size on the axial stress of individual and blend biomass pellets is presented in Figure 4 (a) and (b), respectively.

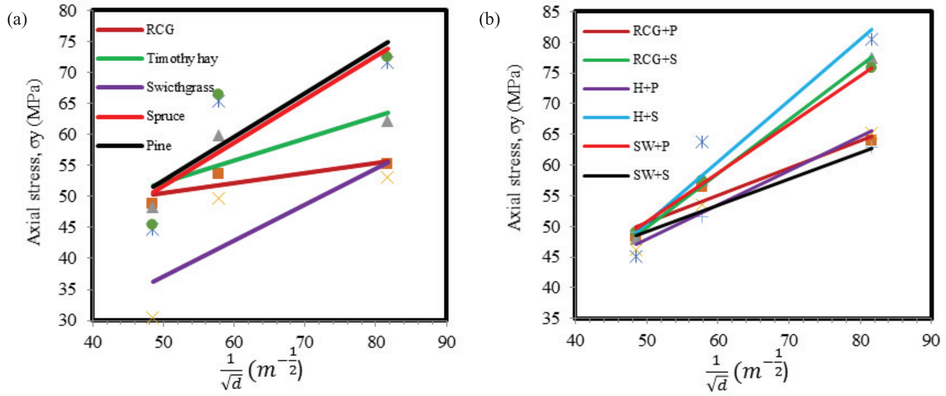


Figure 4. (a) Yield stress relating particle size of individual biomass pellet; (b) Yield stress relating particle size of blended biomass pellet

The particle size relationships with axial stress of pellet made from spruce, pine, reed canary grass, timothy hay and switchgrass fitted the Hall-petch equation. Apparently, its intercept at σ_i, which is the inherent yield stress of spruce (40.5 MPa), pine (41 MPa) and switchgrass (27.4 MPa) was found similar to the value of compressive yield stress found in literature (spruce and pine were ranged 40-46, and switchgrass was 27.7 MPa) [28 and 29]. However, σ_i for RCG and timothy hay was difficult to find from literature. Since σ_i for spruce, pine and swicthgrass fitted well with the value from literature, it is therefore assumed that σ_i for RCG and timothy hay might also work well. The model relating the particle size and the yield strength of the selected biomass and their blend is presented in Table 3.

Table 3. Axial stress and particle size relationship using Hall-petch equation, $\sigma_y = \frac{k}{\sqrt{D}} + \sigma_i$, for biomass pellet, and their mean of means errors

Biomass	Axial stress	R^2
Pine	$\sigma_y = \frac{6.7675}{\sqrt{D}} + 41.154$	0.9084
Spruce	$\sigma_y = \frac{6.6925}{\sqrt{D}} + 40.466$	0.9135
RCG	$\sigma_y = \frac{1.7557}{\sqrt{D}} + 47.834$	0.9215
Timothy hay	$\sigma_y = \frac{3.49}{\sqrt{D}} + 46.3$	0.8755
Switchgrass	$\sigma_y = \frac{5.6775}{\sqrt{D}} + 27.398$	0.8591
RCG+P	$\sigma_y = \frac{3.93}{\sqrt{D}} + 44.51$	0.9995
RCG+S	$\sigma_y = \frac{7.36}{\sqrt{D}} + 38.863$	0.9604
H+P	$\sigma_y = \frac{4.775}{\sqrt{D}} + 40.648$	0.9829
H+S	$\sigma_y = \frac{8.8525}{\sqrt{D}} + 36.639$	0.9989
SW+P	$\sigma_y = \frac{6.6525}{\sqrt{D}} + 40.836$	0.9558
SW+S	$\sigma_y = \frac{3.4475}{\sqrt{D}} + 44.191$	0.8754

The pellets produced from smaller particle size typically depict much higher strength as compared to larger particles. The yiled stress of all blended biomass pellets was found to be approximately 42-47 MPa at higher particle size (~400 µm) as presented in Figure 4 (b). Generally, based on this relationship, blended biomass selected in this study has almost similar mechanical strength property and slightly followed the mechanical strength of woody biomass.

4. Conclusion

In this study the effect of particle size and blending agricultural biomass, to woody biomass on the physical and mechanical properties of the pellet was investigated. Biomass pellets made with smaller particle size showed high yield stress and density. The biomass pellets made from individual or only agricultural biomass are usually low in density (584-799 kg/m^3) depending on particle size. However, a significant improvement in density (627-969 kg/m^3) was achieved after blending them with woody biomass ratio 50:50 and eventually met the pellet quality standard. Nevertheless, the mechanical strength of the biomass pellet was also found to depend on the physical characteristics of biomass such as particle size. The yield stress is in agreement with the density that pellets made from smaller particles size are stronger than pellets made from larger particle size. First and foremost, the mechanical strength of blended biomass pellets was found comparable to that of woody pellets. Blending agricultural biomass with woody biomass to produce pellets can be one of the potential options for the pellet industry. Since agricultural biomass are not only cheap and abundantly available, but blending them with existing woody feedstock showed better improvement in their mechanical and physical properties of the pellet that can meet the pellet fuel quality standards.

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References

[1] Obernberger, I.. and G. Thek. 2004. Physical characteristic and chemical composition of densified biomass fuels with regard to their combustion behavior. Biomass and Bioenergy, 27: 653–669.
[2] Bhattacharya, S. C. 2002. Biomass energy use and densification in developing countries. Paper presented at the ‘‘Pellets 2002: The First World Conference on Pellets’’, Stockholm, Sweden, 2–4 September.
[3] Taylor, R. E., Butzelaar, P., Leeuwen, G. V., Palmer, A., Keyes, J., Gimenez, C. and B. MacDonald. 2013 Wood Pellet Market Outlook. In Wood Market International Monthly Report. 18(1). Available at www. woodmarkets.com
[4] Gogolek, P. and F. Preto. 2000. Status and potential of energy from biomass in Canada. CANMET Energy Technology Centre, Nepean, Ontario, K1A-1M1
[5] Helwig, T, R. Jannasch, R. Samson, A. DeMaio, and D. Caumartin. 2002. Agricultural biomass residue inventories and conversion systems for energy production in Eastern Canada Final Report Prepared for Natural Resources-Canada.
[6] Mani, S., L. Tabil, and S. Sokhansanj. 2006. Effects of Compressive Force, Particle Size, and Moisture Content on Mechanical Properties of Biomass Pellets from Grasses. Biomass and Bioenergy, 30: 648–654.
[7] Tumuluru, J. S., S. Sokhansanj, L. Tabil, M. Kashaninejad, and S. Bandyopadhyay. 2010. Effect of Extrusion Process Conditions on the Quality Attributes of Multi-Component Biomass Pellets. Food and Bioprocess Technology.
[8] Nielsen, N. P. K., D. J. Gardner, T. Poulsen, and C. Felby. 2009. Importance of temperature, moisture content, and species for the conversion process of wood residues into fuel pellets. Wood and Fiber Science. 41: 414-425.
[9] Holm, J. K., U. B. Henriksen, K. Wand, J. E. Hustad, and D. Posselt. 2007. Experimental verification of novel pellet model using a single pelleter unit. Energy & Fuels, 21: 2446-2449.
[10] Wolfgang, S., K. H. Jens, R. S. Anand, B. Soren, A. Jesper, and B. H. Ulrik. 2011. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. Biomass and Bioenergy 5; 910-918.
[11] Sokhansanj, S. and A. F. Turhollow. 2004. Biomass densification - Cubing operations and costs for corn stover. Applied Engineering in Agriculture, 20: 495-499.
[12] Mani, S., S. Sokhansanj, X. Bi, and A. Turhollow. 2006. Economics of producing fuel pellets from biomass. Applied Engineering Agricultural, 22: 421-426.
[13] Dhamodaran, A., and M. T. Afzal. 2012. Compression and Springback Properties of Hardwood and Softwwod Pellets. BioResources. 7(3): 4362-4376.
[14] Harun, N. Y. and M. T. Afzal. 2015. Chemical and Mechanical Properties of Pellets Made from Agricultural and Woody Biomass Blends. Transactions of the ASABE, Vol. 58(4): American Society of Agricultural and Biological Engineers ISSN 2151-0032 DOI 10.13031/trans.58.11027
[15] Kaliyan, N. and R. V. Morey. Densification characteristics of corn stover and switchgrass. Transactions of the ASABE. 2009, 52, 907-920
[16] Senelwa, K. and R. E. H. Sims. 1999. Fuel characteristics of short rotation forest biomass. Biomass Bioenerg, 17: 127–140.
[17] Senneca, O., R. Chirone, P. Salatino, and L. Nappi. 2007. Patterns and kinetics of pyrolysis of tobacco under inert and oxidative conditions. Journal of Analytical Applied Pyrolysis, 79: 227–233.
[18] Lam, P. S., S. Sokhansaj, X. Bi, C. Lim, L. J. Naimi, M. Hoque, S. Mani, A. R. Womac, X. P. Ye, and S. Narayan. 2008. Bulk density of wet and dry wheat straw and dry particles. Applied Engineering Agricultural. 24: 351-358.
[19] Mani, S., L. Tabil, and S. Sokhansanj. 2006. Effects of Compressive Force, Particle Size, and Moisture Content on Mechanical Properties of Biomass Pellets from Grasses. Biomass and Bioenergy, 30: 648–54.
[20] Colley, Z., O. O. Fasina, D. Bransby, and Y. Y. Lee. 2006. Moisture effect on the physical characteristics of switchgrass pellets. Transaction of ASABE, 49(6): 1845-1851
[21] Arzola, N., A. Gómez, and S. Rincón. 2012. The effects of moisture content, particle size and binding agent content on oil palm shell pellet quality parameters. Ingeniería E Investigación, 32(1): 24-29.
[22] Stelte, W., J. K. Holm, A. R. Sanadi, S. Barsberg, J. Ahrenfeldt, and U. B. Henriksen. 2011. A study of bonding and failure mechanisms in fuel pellets from different biomass resources. Biomass Bioenergy, 35(2): 910-918.
[23] Stelte, W., C. Clemons, J. K. Holm, R. A. Sanadi, R. A., Shang, L., Ahrenfeldt, J., and U. B. Henriksen. 2012. Fuel pellets from wheat straw: The effect of lignin glass transition and surface waxes on pelletizing properties. Bioenergy Resources, 5(2): 450-458.
[24] Chia, K. H., K. Jung, and H. Conrad. 2005. Dislocation density model for the effect of grain size on the flow stress of a Ti–15.2 at. % Mo -alloy at 4.2–650 K. Materials Science and Engineering A, 409: 32–38.
[25] Hansen, N. 2004. Hall–Petch relation and boundary strengthening. Scripta Materialia, 51: 801–806.
[26] Meyers, M. A., A. Mishra, and D. J. Benson. 2006. Mechanical properties of nanocrystalline materials. Progress in Materials Science, 51: 427–556.
[27] Kamalanathana , P., S. Rameshan , L.T. Banga , A. Niakana , C.Y. Tana , J. Purbolaksonoa , Hari Chandranb , and W.D. Teng. 2014. Synthesis and sintering of hydroxyapatite derived from eggshells as a calcium precursor. Ceramics International 40: 16349–16359.
[28] Green, D. W., J. E. Winandy, and D. E. Kretschmann. 1999. Mechanical Properties of Wood in Wood handbook—Wood as an engineering material. General Technical Report FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p
[29] Yu, M. 2004. Ultimate Strength Characteristics of Switchgrass Stem Cross-Sections at Representative Processing Conditions. Master Thesis, University of Tennessee, Knoxville.