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Original Article

Effect of Moisture Content of Sawdust and Length to Diameter Ratio of a Hole in Flat-die Pelletizer on The Fuel Characteristics of Wood Pellets Produced with *Quercus mongolica*, *Pinus densiflora*, *Pinus rigida* and *Larix kaempferi*[1]

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ABSTRACT

This study was conducted to identify the potential of *Quercus mongolica* (QUM), *Pinus densiflora* (PID) and *Pinus rigida* (PIR) as a raw material for pellet production. *Larix kaempferi* (LAK), which has mostly been used for pellet production in Korea, was also used as a control. All specimens contained very minimal amounts of sulfur and chlorine. Ash content of LAK was the lowest, followed by PID, PIR and QUM. For the size distribution, the mass fraction between 0.42 mm and 0.25 mm was the highest in PIR. Most fuel characteristics of the produced wood pellets improved with the use of 12% moisture content (MC) particles and the increase of the ratio of length to diameter of a hole in flat-die (L/D ratio). When the MC, bulk density and durability of QUM, PID, PIR and LAK pellets was compared with the standards of the KFRI and ISO, the use of wood particles of 12% MC and flat-die with an L/D ratio of 5.00 for PID particles are suitable for high-quality pellets in the aspects of all fuel characteristics. For PIR and QUM, further work is needed to seek the optimum conditions for the production of high-quality and durable pellets.

Keywords : wood pellet, moisture content, ratio of length to diameter of die hole, bulk density, durability

1. INTRODUCTION

During the past 20 years, there has been increasing interest in the use of wood pellets alternative to fossil fuels for heat and power generation. For example, global consumption of wood pellets in 2008 was 11 million tons on an oven-dry basis, and the figure is projected to increase to more than 22 million tons by 2014 (IWMG, 2010). In South Korea, wood pellet production began in a plant operated by the National Forestry Cooperative Federation in 2009, and demand for wood pellets as a source of energy are expected to increase greatly in the near future (Han, 2014).

Most of the land in South Korea is included

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in the temperate climatic zone. *Quercus mongolica* (Mongolian oak), *Pinus densiflora* (red pine), *Pinus rigida M.* (pitch pine) and *Larix kaempferi* (larch) are the major species growing on the land, making up approximately 72 percent of total growing-stock volume (Korea Forest Service, 2014). Among the species, for the production of wood pellets, larch has mostly been used until a recent date because wood pellets produced with the sawdust have high durability and calorific value (Ahn *et al*., 2014; Lee *et al*., 2013). On the other hand, Mongolian oak, red pine and pitch pine have hardly been used for producing wood pellets despite their easy availability. The reasons are as follows; 1) Mongolian oak and red pine have extensively been used as raw materials for the productions of furniture, palettes and plywood, and consequently its average prices are higher than that of larch (Fugita and Sano, 2000) it is well known that pitch pine is inappropriate to be used as a raw material for wood pellet production due to its high resin content (Shi *et al*., 2011) most importantly, wood pellets fabricated with Mongolian oak and red pine had lower qualities than those with larch, when produced with the same pelletizing conditions for larch pellets. For example, durability and bulk density of pellets produced with Mongolian oak and red pine were lower than those of larch (Kim *et al*., 2015). These results are probably due to the differences of physicochemical properties in wood particles used for pellet productions. Each wood species used as raw material has its own specific polymeric characteristics, and thus will be applied specific temperature, pressure and moisture characteristics to form a pellet. Therefore, the pelletizing process is quite material specific (Brackley and Parrent, 2011), and consequently it is necessary to find optimal pelletizing conditions for using Mongolian oak, red pine and pitch pine as raw materials of wood pellets with acceptable durability and bulk density.

Fuel characteristics of wood pellets depend upon the physiochemical properties, size and shape of wood particles used for producing wood pellets. Hence, a lot of research has been conducted to investigate the numerous factors affected affecting fuel characteristics of wood pellets, including production parameters and equipment processing variables. For example, chemical composition, size and moisture content of wood particles, steam conditioning and preheating of feed, addition of binders and densification equipment variables (forming pressure, die dimension and speed, gap between roller and die, etc.) on the fuel characteristics of wood pellets have been extensively investigated (Ahn *et al*., 2014; Bergström *et al*., 2008; Brackley and Parrent, 2011; Kaliyan and Morey, 2009; Lee *et al*., 2013; Lehtikangas, 2001; Li and Liu, 2000; Mani *et al*., 2006; Obernberger and Thek, 2004; Stakl *et al*., 2004).

Although several studies related to the production of wood pellets have been conducted in South Korea, no studies have been provided any information relative to the pellet production from Mongolian oak, red pine and pitch pine.

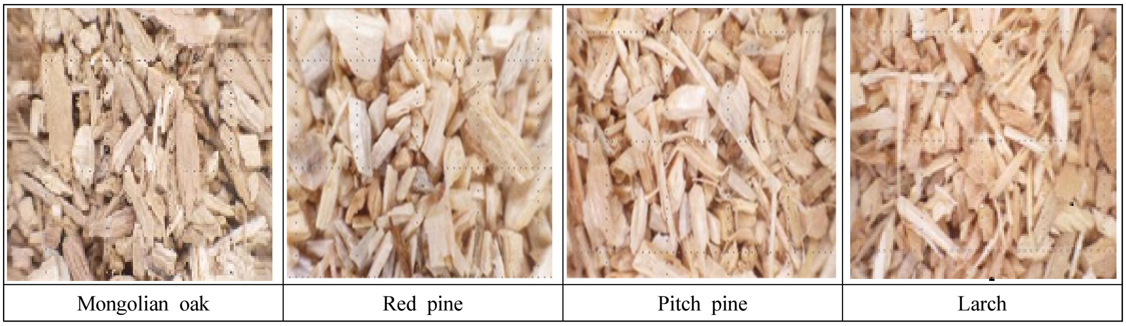

Fig. 1. Images of wood particles used for pellet production.

Therefore, in the present work, wood pellets were produced with Mongolian oak, red pine, pitch pine and larch using by a pilot-scale flat-die pelletizer, and the effects of wood species, moisture content of the wood particles and the ratio of length to diameter of a hole in flat-die on the fuel characteristics of the produced wood pellets were examined. In addition, chemical composition, size distribution of wood particles and elemental analysis of each raw material were measured to investigate the relationship between the physicochemical properties of the wood particles and the fuel characteristics of wood pellets produced with the wood particles.

2. MATERIALS and METHODS

2.1. Raw Materials

Mongolian oak (*Quercus mongolica*, QUM), Korean red pine (*Pinus densiflora*, PID), pitch pine (*Pinus rigida*, PIR) and Japanese larch (*Larix kaempferi*, LAK) were used as raw materials for pellets production. QUM, PID, PIR and LAK were initially harvested throughout Kyungki and Gangwon districts in South Korea, debarked and cut into logs. The logs were then ground into wood particles using by chopping mill (YM-450BM, Yulim Co. Ltd., Gyeongsan, South Korea) installed at the central distribution center of the National Forestry Cooperative Federation (Yeoju, South Korea), and then the wood particles were dried in large-sized dryer. A moisture level of the wood particles ranged from 6.1% to 13.1% depending on the species. Hereinafter, we will refer to the mass fraction of water as moisture content (MC). The wood particles were transported to Chungbuk National University (Cheongju, South Korea), and then screened through a sieve with size opening 6.4 mm (4 mesh). The wood particles were humidified by spraying water or dried in medium-sized dryer (for tobacco leaves) to adjust to MC of 10%. The wood particles were used as raw materials in the pelletizing process (Fig. 1).

QUM, PID, PIR and LAK particles were pulverized to powder using a Polytron medium-capacity homogenizer (PT-MR 2500 E; Kinematica AG; Lucerne, Switzerland), and then screened through a sieve with size opening of 0.42 mm (60 mesh). The fine powder passed through the sieve was used to analyze elemental and chemical compositions as well as to identify the ash content and calorific value of QUM, PID, PIR and LAK.

2.2. Elemental Analysis

For the elementary analysis, a fine powder of 2 mg was put into the reactor chamber and combusted at the temperature of 990℃, with a sufficient supply of oxygen (Yang *et al*., 2016). The fine powder was converted into a gas mixture with complete oxidation. The gas mixture was passed to a gas chromatographic system with helium gas as a carrier gas, and separated into CO_2, N_2, H_2O and SO_2 gases. Each gas was transformed to an electrical signal using a thermal conductivity detector. The calibration of each gas was done through the elementary analysis of standard samples provided by the instrument manufacturer, and then the contents of carbon, hydrogen, nitrogen and sulfur were measured (Flash 2000 Organic Elemental Analyzer, Thermo Fisher Scientific, Waltham, USA). The amount of chlorine content was determined by the inductively coupled plasma - atomic emission spectroscopy (ICP - AES, Optima 4300 DV, PerkinElmer, Waltham, USA). The results of elementary analysis were calculated based on the average of three measurements.

2.3. Quantitative and Qualitative Analysis of Ash

For the measurement of ash contents, 1 g of the oven-dried fine powder was placed into a dried and pre-weighed porcelain crucible, and then burned away the specimen in the muffle furnace at 575℃ for 6 h (ASTM, 2005a). The crucible was weighed after cooling to room temperature in a desiccator. Ash content was calculated as the ratio of weights of ash and original specimen.

Qualitative analysis of ash contained in each specimen was measured according to the standard for the quality of wood pellets designated by the National Institute of Forest Science (NIFOS, 2016). For instance, fine powder of each specimen (0.5 g) was dissolved by 65% nitric acid solution, and then the insoluble constituent was separated on a glass filter (1G4). Subsequently, chromium (Cr), lead (Pb), nickel (Ni) and zinc (Zn) included in the insoluble constituent were analyzed by ICP - AES, and arsenic (As), cadmium (Cd), mercury (Hg) and copper (Cu) by ICP - mass spectrometry (ICP - MS).

2.4. Calorific Value

The adiabatic oxygen bomb calorimeter (Parr 6400 Automatic Isoperibol Calorimeter, Parr Instrument Inc., Moline, Illinois, USA) was used for the determination of calorific value of each specimen based on the standard for the quality of wood pellet designated by the NIFOS

(2016). Initially, 1 g of each specimen was placed in a nickel crucible and burned inside the bomb calorimeter. The specimen was ignited by a pure cotton thread in the presence of oxygen. Upon the ignition, the released heat was transferred to the temperature sensor (White, 1987; Kim *et al*., 2010). The increase in temperature was used to calculate the calorific value of the specimen. The calorific value was expressed in MJ/kg. Each specimen was tested three times to obtain most accurate results.

2.5. Analysis of Chemical Composition

Moisture content of each specimen was determined using an oven-drying method (ASTM, 2005b). For the determination of holocellulose and lignin contents, standard procedures of the Association of Official Analytical Chemists and National Renewable Energy Laboratory were used, respectively (A.O.A.C., 1990; Effland, 1977).

2.6. Particle Size Distribution

Size distribution of wood particles, which were ground, screened and then dried to 10% MC, was determined by a Rio-Tap sieve shaker (CG - 211 - 8, Tyler Industrial Products, U.S.A.). Sieves of 18, 40 and 60 meshes with corresponding opening size of 1.00, 0.42 and 0.25 mm, respectively, were used for wood particles passed through the screen of 6.4 mm size. Sieving time was controlled at 10 min for each test. Each specimen was tested ten times to obtain most accurate results.

2.7. Pellet Production

Prior to pelletizing, the wood particles dried to MC of 10% was humidified to 12% MC to examine the relationship between MC of wood particles and the MC, bulk density and durability of wood pellets. For the humidification, 10% MC particles of 10 kg were spread on the large tray, and then the tray was put on a scale. After that, 200 g of de-ionized water was sprayed on the particles of the tray for fixing the MC of wood particles to 12%, respectively. The particles, which were adjusted to MC, were placed in a sealable plastic bag and stored in refrigerator before being analyzed.

Wood particles were converted to pellets by using a flat-die pelletizer (engine power: 15 kW) developed by Sun Brand Industrial Co., Ltd. (Damyang, Jeonnam). Production rate for the pelletizer is approximately 130 kg/h. Die of the pelletizer has 192 holes with a diameter of 6 mm and a length of 29, 30 and 31 mm, and thus the ratios of length to diameter of a hole in flat-die (L/D ratio) were 4.83, 5.00 and 5.17, respectively. The pelletizer also consists of two rollers with a diameter of 18.5 cm. There was no gap between the rollers and die, and rotating speed of the rollers was adjusted to 98.4 rpm. The average diameter of wood pellets fabricated with the pelletizer ranged from 6.3 mm to 6.8 mm. Average length of the wood pellets varied with the L/D ratio and type of wood particles.

The produced wood pellets were collected at 10-minute intervals, and then placed in an incubation room (25℃ and 50% RH) for at least 24 h before testing the fuel characteristics of wood pellets.

2.8. Moisture Content, Bulk Density and Durability Tests for Wood Pellets

Moisture content of the produced wood pellets was determined using an oven-drying method (ASTM, 2005b). Bulk density measurement of wood pellets was performed according to ASABE S269.5 (ASABE, 2012). For instance, wood pellets were filled by pouring into a cylindrical container of 5-liter volume (diameter: 16.7 cm; height: 22.8 cm) from a height of 61 cm above the top edge of the container. After that, excess wood pellets on top of the container were scraped off with a straight edge. For tapped density, the loosely filled container was tapped on the laboratory bench three times in a vertical direction to allow settling, and then the weight of the filled container was recorded. Bulk density of the wood pellets was determined from the resulting weights (Yang *et al*., 2015). The measurement of bulk density was repeated three times.

For the measurement of durability, 500 g of wood pellets were placed in a tumbling can and tumbled at 50 rpm for 10 min. Subsequently, the tumbled pellets were sieved through a 0.5-mm sieve to remove crumbs attached on the surface of wood pellets, and then weighed to the nearest thousandth of a gram. The durability of the wood pellets was calculated as the ratio of the weight after tumbling to that before tumbling (NIFOS, 2016).

2.9. Experimental Design and Statistical Analysis

The effects of wood species (QUM, PID, PIR and LAK), moisture content (10 and 12%) and L/D ratio (4.83, 5.00 and 5.17) on the fuel characteristics of the produced wood pellets were examined first. A factorial design (4 × 2 × 3) was adopted as the experimental design in this study.

The statistical analysis was carried out using the SAS software package for personal computers. One-way analysis of variance (ANOVA) was used to analyze the effects of each variable on the moisture content, bulk density and durability of pellets at a 0.05% level of significance. If a significant effect was found in a variable, the Student t-test was used to determine any significant difference between the moisture contents, bulk densities and durabilities of the wood pellets produced under each condition (α = 0.05).

3. RESULTS and DISCUSSION

3.1. Elements Contents

The elemental analysis of QUM, PID, PIR and LAK is given in Table 1. Carbon content of PIR was the highest followed by LAK, PID and QUM. From these results, it could confirm

Table 1. Ultimate and calorific content (CV) analysis of Mongolian oak (*Quercus mongolica*), red pine (*Pinus densiflora*), pitch pine (*Pinus rigida*) and larch (*Larix kaempferi*) used in this study

Biomass	Elemental content (%)						CV (MJ/kg)
	C	H	N	S	Cl	Ash	
Mongolian oak	48.9 (0.3)	6.8 (0.1)	0.1 (< 0.1)	< 0.01 (< 0.01)	< 0.01 (< 0.01)	0.6 (0.1)	19.1 (0.4)
Red pine	49.8 (0.2)	6.8 (0.1)	< 0.1 (< 0.1)	< 0.01 (< 0.01)	< 0.01 (< 0.01)	0.3 (< 0.1)	20.9 (0.1)
Pitch pine	50.6 (0.2)	7.1 (0.1)	< 0.1 (< 0.1)	< 0.01 (< 0.01)	< 0.01 (< 0.01)	0.4 (0.1)	20.6 (0.3)
Larch	50.0 (0.1)	7.0 (0.1)	< 0.1 (< 0.1)	< 0.01 (< 0.01)	< 0.01 (< 0.01)	0.2 (< 0.1)	20.2 (< 0.1)
NIFOS 1st-grade[a]	-	-	< 0.3	< 0.05	< 0.05	≤ 0.7	≥ 18.0
ISO A1 grade[b]	-	-	< 0.3	< 0.03	< 0.02	≤ 0.7	16.5 ≤ Q ≤ 19.0

Number in parenthesis is a standard deviation of mean for the element content, ash content and calorific value of each biomass.
[a] This indicates the specification of 1st-grade wood pellets in the standard designated by National Institute of Forest Service.
[b] This indicates the specification of A1-grade wood pellets in the standard designated by International Organization for Standardization (ISO 17225-2).

that higher lignin and extractives contents of softwood compared to those of hardwood is closely associated with the higher carbon content of PIR, LAK and PID (Regland and Aerts, 1991). All specimens contained approximately 7% hydrogen, but PIR and LAK contained more hydrogen than PID and QUM (Pentura, 1979). On the other hand, QUM had more nitrogen than PID, PIR and LAK, but there were no differences among the nitrogen contents of PID, PIR and LAK. Additionally, traces of sulfur and chlorine were detected in all specimens. Contents of nitrogen, sulfur and chlorine contained in all specimens easily met the specifications of NIFOS standard for 1st-grade wood pellets and International Organization for Standardization (ISO) standard for A1-grade wood pellets (NIFOS, 2016; IOS, 2014).

3.2. Ash Content

Table 1 also shows the amount of ash contained in each specimen. Ash content of LAK was the lowest, followed by PID, PIR and QUM. However, ash content of all specimens tested in this study satisfied the standards of NIFOS for 1st-grade and ISO for A1-grade wood pellets (NIFOS, 2016; IOS, 2014).

When the ashes were qualitatively analyzed, no arsenic and mercury was found in any specimens, and no nickel in PID and PIR were detected (Table 2). On the other hand, cadmium, chrome, copper, lead and zinc were found in all specimens, but the amounts were greatly below the specifications of NIFOS standard for 1st-grade and ISO standard for A1-grade wood pellets (NIFOS, 2016; IOS, 2014).

Table 2. Qualitative analysis of Mongolian oak (*Quercus mongolica*), red pine (*Pinus densiflora*), pitch pine (*Pinus rigida*) and larch (*Larix kaempferi*) used in this study (Unit: mg/kg)

Biomass	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
Mongolian oak	ND	0.1 (< 0.1)	1 (< 0.1)	2 (< 0.1)	1 (< 0.1)	ND	< 0.1 (< 0.1)	3 (< 0.1)
Red pine	ND	0.2 (< 0.1)	1 (< 0.1)	2 (< 0.1)	1 (< 0.1)	ND	ND	6 (< 0.1)
Pitch pine	ND	0.2 (< 0.1)	1 (< 0.1)	2 (< 0.1)	1 (< 0.1)	ND	ND	8 (< 0.1)
Larch	ND	0.1 (< 0.1)	2 (< 0.1)	2 (< 0.1)	1 (< 0.1)	ND	< 0.1 (< 0.1)	4 (< 0.1)
NIFOS 1st-grade[a]	≤ 1.0	≤ 0.5	≤ 10	≤ 10	≤ 10	≤ 0.05	≤ 10	≤ 100
ISO A1 grade[b]	≤ 1.0	≤0.5	≤ 10	≤ 10	≤ 10	≤ 0.1	≤ 10	≤ 100

ND means that each element was not detected.
[a] This indicates the specification of 1st-grade wood pellets in the standard designated by National Institute of Forest Service.
[b] This indicates the specification of A1-grade wood pellets in the standard designated by International Organization for Standardization (ISO 17225-2).

3.3. Calorific Value

Average calorific values of QUM, PID, PIR and LAK are presented in Table 1. PID showed the highest calorific value followed by PIR, LAK and QUM, but the calorific value of PID did not differ statistically from that of PIR. The low calorific value of QUM is probably due to its low carbon and lignin contents, as shown in Tables 1 and 3. In general, calorific value of a lignocellulosic material is proportional to its carbon and lignin contents (Cordero *et al*., 2001; Dhamodaran, *et al*., 1989; White, 1987). Contents of lignin and carbon contained in QUM were lower than those of PID, PIR and LAK, and consequently calorific value of QUM might be lower than those of PID, PIR and LAK. However, calorific values of all specimens were higher than that of the specifications of NIFOS standard for 1st-grade and ISO standard for A1-grade wood pellets (NIFOS, 2016; IOS, 2014).

3.4. Chemical Composition

Table 3 presents the chemical composition of QUM, PID, PIR and LAK. Amounts of holocellulose, lignin and extractives included in each specimen did not differ largely from those of other studies. For instance, QUM, which was used solely as a hardwood in this study, exhibited higher holocellulose content than PID, PIR and LAK. Among the softwood specimens, PID contained more holocellulose than LAK, and the holocellulose content of PIR was the lowest. On the contrary, QUM had a low lignin content, and PIR was found to have a high lignin content. For extractives content, LAK was the highest followed by PIR, PID and QUM. However, the content of organic compounds, such as terpenoids, fats and phenolic substances, extracted by acetone was the highest in

Table 3. Chemical composition of Mongolian oak (*Quercus mongolica*), red pine (*Pinus densiflora*), pitch pine (*Pinus rigida*) and larch (*Larix kaempferi*) used in this study

Biomass	Holocellulose	Lignin	Extractives		
			Total	Hot water	Acetone
Mongolian oak	75.5 (A)	24.1 (C)	8.0 (C)	7.1	0.9
Red pine	68.5 (B)	30.7 (B)	8.0 (C)	5.0	3.0
Pitch pine	64.9 (D)	31.9 (A)	9.2 (B)	5.9	3.3
Larch	66.9 (C)	30.7 (B)	12.3 (A)	9.8	2.5

Same capital letters in each column are not significantly different from each other at p = 0.05 (Student t-test).

Table 4. Overall fuel characteristics of wood pellets produced with flat-die pelletizer

Biomass	Moisture content (%)	Bulk density (kg/m^3)	Durability (%)
Mongolian oak	7.4 (B)	655 (B)	96.0 (A)
Red pine	7.7 (C)	651 (B)	96.2 (A)
Pitch pine	7.5 (B)	613 (D)	91.8 (B)
Larch	6.5 (A)	680 (A)	96.4 (A)
NIFOS 1st-grade[a]	≤ 10.0	≥ 640	≥ 97.5
ISO A1 grade[b]	≤ 10.0	≥ 600	≥ 97.5

Same capital letters in each column are not significantly different from each other at p = 0.05 (Student t-test).
[a] This indicates the specification of 1st-grade wood pellets in the standard designated by National Institute of Forest Service.
[b] This indicates the specification of A1-grade wood pellets in the standard designated by International Organization for Standardization (ISO 17225-2).

PIR and the lowest in QUM, respectively (Sjostrom and Alen, 1989). The organic compounds might be closely related to the increase of calorific value, and consequently the high content of the acetone-extracted organic compounds in PIR and PID seems to contribute to its higher calorific value compared to LAK.

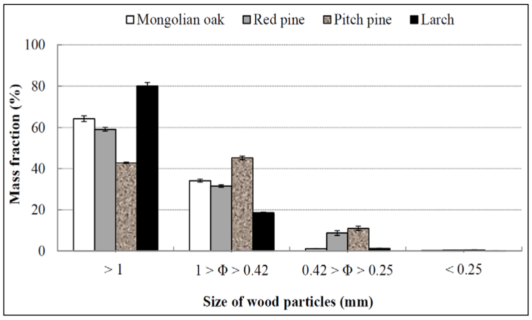

Fig. 2. Size distribution of four size group of wood particles used for pellet production. Error line on each bar means the standard deviation of the measured mean.

3.5. Particle Size Distribution

Particle size, along with moisture content, is one of the most significant factors affecting overall pellet quality. Fig. 2 shows the mass fraction of four groups of sizes for wood particles used for pellets production. For the size category > 0.1 mm, the mass fraction of LAK was the most followed by QUM, PID and PIR. For the size category between 0.1 mm and 0.42 mm, on the contrary, PIR showed the highest mass fraction followed by QUM, PID and

LAK. For the size category between 0.42 mm and 0.25 mm, the mass fraction of PIR was the most, and that of QUM and LAK was the least. For the finest size category of < 0.25 mm, the mass fraction of PIR and PID was the most followed by QUM and LAK. These results indicate that the size of wood particle ground by chopping mill is greatly influenced by type of wood species.

3.6. Fuel Characteristics of Wood Pellets

Table 4 lists the average moisture content, bulk density and durability of wood pellets produced in this study. The fuel characteristics varied with the type of wood species. These results indicate that fuel characteristics of wood pellets might be influenced by the physiochemical properties and shape of QUM, PID, PIR and LAK particles, because the wood pellets were produced under the same MC (10 and 12%), particle size (< 6.4 mm) and the ratio of length to diameter of a hole in the flat-die of a pelletizer (L/D ratio: 4.83, 5.00 and 5.17) except for the wood species.

For MC, PID pellets was the highest followed by PIR, QUM and LAK pellets. The higher MC of PID and PIR pellets is probably associated with the higher content of acetone-extracted organic compounds existed in PID and PIR as shown in Table 3. For instance, it seems that the extractives have a negative impact on the migration of moisture in PID and PIR particles during the pelletizing process. For bulk density and durability, LAK pellets showed the highest, and PIR pellets the lowest (Table 4). The low durability of PIR pellets is probably due to higher fine particle content of PIR compared to other specimens (Fig. 2). For instance, durability of PIR pellets seems to be influenced more by fine particles than by large particles. Therefore, in future work, durability of wood pellets produced from PIR particles with broad ranges of size will be measured to confirm the relationship between the amount of fine particles and the durability of the pellets. Overall, we recognized that fuel characteristics of wood pellets is influenced by the physiochemical properties, MC and shape of wood particles as well as the shape of the produced wood pellets. Therefore, the effects of MC of wood particles and the L/D ratio on the MC, bulk density and durability of QUM, PID, PIR and LAK pellets were investigated.

3.6.1. Effect of moisture content of wood particles

As shown in Fig. 3 and Table 5, MC of QUM, PID and LAK pellets increased when MC of the wood particles increased from 10% to 12%. These were natural consequences that higher MC of wood particles resulted in higher MC of the respective pellets. However, MC of PIR particles did not impact on the MC of PIR pellets.

Bulk densities of QUM and LAK pellets decreased as the MC of wood particles increased from 10% to 12% (Fig. 4 and Table 5). The results are likely to be closely related to the anatomical properties of QUM and LAK. In other words, QUM and LAK have a high specific

Table 5. Statistical analysis of moisture content, bulk density and durability of wood pellets produced with Mongolian oak, red pine, pitch pine and larch particles as a function of moisture content of wood particles (W-MC), the ratio of length to diameter of a hole in flat-die (L/D) and its interaction (W-MC × L/D)

Source	DF	Moisture content		Bulk density		Durability	
		F value	Pr > F	F value	Pr > F	F value	Pr > F
Mongolian oak							
W-MC	1	5.80	0.006	27.91	< 0.001	10.45	< 0.001
L/D	2	10.12	< 0.001	5.09	0.015	4.08	0.019
W-MC × L/D	2	1.96	0.142	4.73	0.019	1.88	0.154
Red pine							
W-MC	1	6.17	0.002	1.27	0.238	17.47	< 0.001
L/D	2	3.46	0.032	3.99	0.021	3.14	0.037
W-MC × L/D	2	1.78	0.169	1.19	0.296	1.17	0.302
Pitch pine							
W-MC	1	1.95	0.140	3.13	0.058	23.39	< 0.001
L/D	2	4.71	0.009	3.47	0.025	4.78	0.008
W-MC × L/D	2	1.29	0.276	1.92	0.151	1.79	0.170
Larch							
W-MC	1	30.78	< 0.001	25.16	< 0.001	12.83	< 0.001
L/D	2	3.09	0.044	11.77	< 0.001	1.71	0.086
W-MC × L/D	2	1.61	0.200	5.51	0.009	1.99	0.129

gravity (QUM: SG_{true} = 0.78; LAK: SG_{true} = 0.56) and possess thick cell wall compared to PIR (SG_{true} = 0.49) and PID (SG_{true} = 0.44) (Yang *et al*., 2015; Jeong and Park, 2007). Therefore, during a pelletizing process, QUM or LAK particles need more heat energy to evaporate moisture existing in the cell wall to a certain level than PIR and PID particles do. However, pelletizing conditions applied to QUM and LAK particles of 12% MC seem to be inadequate for pellet production, and thus the pellets had high MC. Consequently, when QUM and LAK pellets produced with 12% MC particles get out from the die-hole of pelletizer, wood particles composed the pellets might expand partly due to the excessive moisture remained in the pellets resulting in the decrease of bulk density. Meanwhile, increasing the MC of PID and PIR particles did not affect the bulk densities of the respective pellets (Fig. 4 and Table 5).

With the increase of wood particle MC, as shown in Fig. 5 and Table 5, durabilities of all pellets produced in this study increased. Several studies showed that durability of wood pellets increased with increasing the MC of particles until an optimum is reached (Obernberger and Thek, 2004; Li and Liu, 2000; Lee *et al*., 2013). Accordingly, durable pellets might be produced as MC of wood particles increased.

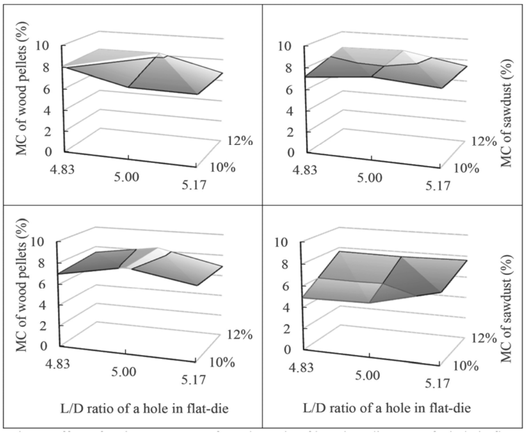

Fig. 3. Effect of moisture content of sawdust and ratio of length to diameter of a hole in flat-die pelletizer on the moisture content of wood pellets produced with Mongolian oak (top-left), red pine (top-right), pitch pine (bottom-left) and larch (bottom-right) particles.

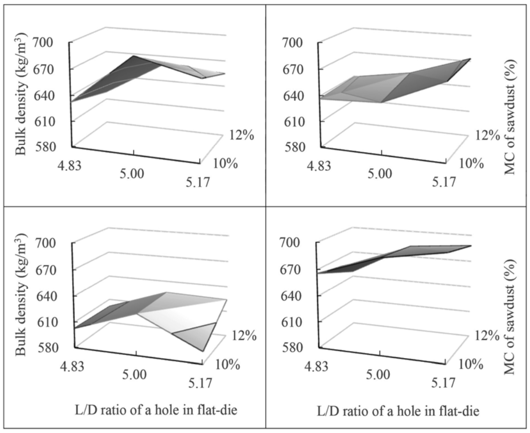

Fig. 4. Effect of moisture content of sawdust and ratio of length to diameter of a hole in flat-die pelletizer on the bulk density of wood pellets produced with Mongolian oak (top-left), red pine (top-right), pitch pine (bottom-left) and larch (bottom-right) particles.

Based on the results, however, it is thought that the use of wood particles of 12% MC and higher in pellets production is necessary to elucidate the distinct relationship between the MC of QUM, PID, PIR and LAK particles and the durability of wood pellets produced with the particles.

3.6.2. Effect of the ratio of length to diameter of a hole in flat-die

In this study, the higher L/D ratio means the supply of more heat delivered to the wood particles. Therefore, the higher the L/D ratio, the lower the MC of the produced wood pellets. MC of QUM ($p < 0.01$), PID (4.83/5.00: $p = 0.10$; 4.83/5.17: $p = 0.04$; 5.00/5.17: $p < 0.01$) and PIR (5.00/5.17: $p < 0.01$) pellets decreased by increasing the L/D ratio as shown in Fig. 3 and Table 5. However, MC of LAK pellets produced with the die of 5.17 L/D ratio was higher than that with the die of 4.83 or 5.00 L/D ratio ($p < 0.01$). Since the LAK pellets were produced and tested in rainy season, the pellets seem to show high moisture content.

For bulk density, the values of QUM (4.83/5.00 & 4.83/5.17: $p < 0.01$; 5.00/5.17: $p = 0.06$), PID (4.83/5.00: $p = 0.15$; 4.83/5.17 & 5.00/5.17: $p < 0.01$) and LAK ($p < 0.01$) pellets increased, or did not change significantly, with the increase of L/D ratio (Fig. 4). In addition, bulk density of PIR pellet increased as the L/D ratio increased from 4.83 to 5.00 ($p < 0.01$). The results are due to the increase of shear force applied to wood particles, which may positively affect the pellet durability, by the increase of L/D ratio (Kaliyan and Morey, 2009). However, bulk density of the PIR pellets decreased as the L/D ratio increased from 5.00 to 5.17 ($p = 0.01$). The result is probably due to the distinctive shape of PIR particles. For instance, as shown in Fig. 1, PIR particles ground with a chopping mill had more slender particles with a needle-type than QUM, PID and LAK particles, and thus the edge of the produced PIR pellets was saw-toothed resulting in decreases in its bulk density and durability. Particularly, such phenomenon was growing when PIR pellets were produced with the die of 5.17 L/D ratio. In order to identify the speculation, the study of relationship between the shape of wood particles and fuel characteristics of the respective pellets is currently conducted by measuring the length and width of wood particles using an Active Measuring program.

L/D ratio did not impact on the durability of LAK pellets as show in Fig. 5 and Table 5 On the other hand, durabilities of QUM, PID and PIR pellets increased when the L/D ratio increased from 4.83 to 5.00 ($p < 0.01$). The results correspond that the larger the die L/D ratio, the higher the pellet durability (Kaliyan and Morey, 2009). However, with the further increase of the L/D ratio to 5.17, durabilities of QUM ($p = 0.03$) and PIR ($p < 0.01$) pellets decreased, and that of PID pellets was not influenced ($p = 0.29$). The reductions of QUM and PIR pellets might be attributed to the distinctive shape of the pellets. For example, the average length of QUM pellets (19.3 mm) produced with the die of 5.17 L/D ratio was longer than PID (18.8 mm), PIR (18.6 mm) and LAK (18.1 mm) pellets. Hence, the longer length might have a negative effect on the durability of QUM pellets. In the case of PIR pellets, the durability is likely to be reduced by the saw-toothed shape of its edge as mentioned above. However, these assumptions need to be identified in future studies using a flat-die with holes of various lengths in the production of QUM and PIR pellets.

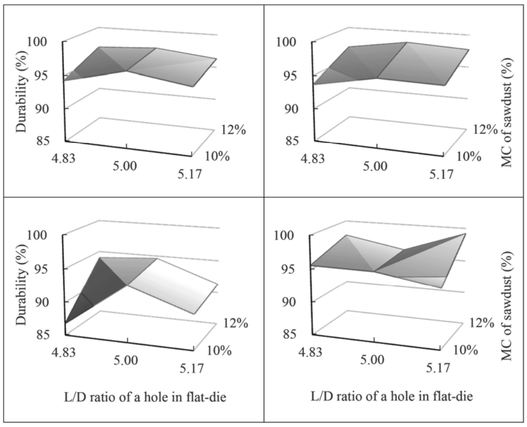

Fig. 5. Effect of moisture content of sawdust and ratio of length to diameter of a hole in flat-die pelletizer on the durability of wood pellets produced with Mongolian oak (top-left), red pine (top-right), pitch pine (bottom-left) and larch (bottom-right) particles.

3.6.3. Interactive effect of wood particles MC and L/D ratio

When the effect of the L/D ratio within a certain MC of wood particles on the MC, bulk density and durability of the produced pellets was compared, significant differences were found only in the bulk densities of QUM and LAK pellets (Table 5). For example, as the L/D ratio increased from 4.83 to 5.00, bulk density of pellets produced with QUM particles of 10% MC increased more than that of 12% MC. In addition, bulk density of the LAK pellets produced with wood particles of 10% MC increased more than that of 12% MC, when L/D ratio increased from 5.00 to 5.17. The results indicate that MC of wood particles is a more significant factor for determining the bulk density of pellets produced with wood particles of a high specific gravity, such as QUM or LAK, than the L/D ratio.

Specifications, of both the NIFOS and ISO standards, call for the 1st- and A1-grade wood pellets of MC to be less than 10%. MC of all pellets produced in this study did not exceed 10%. For the 1st- and A1-grade wood pellets of NIFOS and ISO standards, bulk density is required to be higher than 640 and 600 kg/m^3, respectively. Bulk densities of all LAK pellets and QUM and PID pellets produced with the L/D ratio of 5.00 or 5.17 exceeded 640 kg/m^3, and thus met the 1st- and A1-grade specifications of NIFOS and ISO standards. For PIR pellets, meanwhile, the bulk density values fall outside the 1st- and A1-grade limits specified in the NIFOS and ISO standards without reference to any MC of wood particles and the L/D ratio. Furthermore, PIR pellets produced with wood particles of 10% MC and the L/D ratio of 4.83 could not earn any grades in the ISO standard and satisfied just the specification of 3rd-grade wood pellets in the NIFOS standard. When durabilities of QUM, PID, PIR and LAK pellets were compared with the standards of the NIFOS and ISO, LAK pellets produced with particles of 12% MC and the L/D ratio of 4.83 or 5.17 met the specifications for the durability of the 1st- and A1-grade wood pellets (≥ 97.5%). In addition, durabilities of PID pellets produced with wood particles of 12% MC and the L/D ratio of 5.00 or 5.17 exceeded the minimum requirement for the 1st- and A1-grade wood pellets. However, durabilities of QUM pellets produced with 12% MC particles and those with 10% MC particles and the L/D ratio of 5.00 satisfied just the standards for the 3rd-grade pellets of NIFOS (≥ 95%) and the B-grade pellets of ISO (≥ 96.5%). For PIR pellets, all durability values failed to exceed the ISO minimum requirement for the B-grade pellets, but met the acceptance level for the 3rd-grade pellets of NIFOS. Based on the results, the uses of wood particles of 12% MC and flat-die with an L/D ratio of 5.17 for LAK particles and of 5.00 for PID particles are suitable for high-quality pellets in the aspects of all fuel characteristics. On the other hand, the range of particles MC and L/D ratio used in this study for the production of PIR pellets are not appropriate to produce wood pellets.

4. CONCLUSION

This study was conducted to identify the potential of QUM, PID and PIR as raw materials for pellet production. LAK, which has mostly been used for pellet production in Korea, was also used as a control. Carbon content of PIR was the highest followed by LAK, PID and QUM. QUM had more nitrogen than PID, PIR and LAK. All specimens contained very minimal amounts of sulfur and chlorine. Ash content of LAK was the lowest, followed by PID, PIR and QUM. PID and PIR showed the highest calorific value followed by LAK and QUM. The highest content was measured in QUM for holocellulose, in PIR for lignin and in LAK for extractives, respectively. For the size distribution, the mass fraction between 0.42 mm and 0.25 mm was the highest in PIR.

Fuel characteristics of wood pellets produced in this study varied with the type of wood species. For example, MC of PID pellets was the highest, but LAK pellets showed the highest bulk density and durability. With the increase of MC of wood particles, MC and durability of most pellets increased, but bulk densities of QUM and LAK pellets decreased. Fuel characteristics of most pellets tested in this study improved with the increase of the L/D ratio. However, bulk density and durability of PIR pellets decreased when L/D ratio increased from 5.00 to 5.17. When the effect of the L/D ratio within a certain MC of wood particles on the MC, bulk density and durability of the produced pellets was compared, significant differences were found only in the bulk densities of QUM and LAK pellets. The results indicate that MC of wood particles is a more significant factor for determining the bulk density of pellets produced with wood particles of a high specific gravity, such as QUM or LAK, than the L/D ratio. When the MC, bulk density and durability of QUM, PID, PIR and LAK pellets was compared with the standards of the KFRI and ISO, the use of wood particles of 12% MC and flat-die with an L/D ratio of 5.17 for LAK particles and of 5.00 for PID particles are suitable for high-quality pellets in the aspects of all fuel characteristics. For PIR and QUM, further works are needed to seek the optimum conditions for the production of high-quality and durable pellets.

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