

# Effects of The Torrefaction Process on The Fuel Characteristics *Larix kaempferi* C<sup>1</sup>

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## ABSTRACT

The aim of this study was to evaluate the fuel characteristics of thermally treated wood chips of the *Larix kaempferi* C. As torrefaction temperature was increased (200°C to 300°C), the carbon content, calorific value, and mass loss of torrefied wood chips increased significantly. The torrefied wood chips were shown to have hydrophobic properties even when only treated by mild torrefaction. The energy required to grind torrefied wood chips was reduced by the torrefaction process. Different sizes of wood chips were used in this study; however, this produced almost no difference in the fuel characteristics of processed *Larix kaempferi* C, except in the distribution of ground wood particles. Similar results were observed when the wood chips were torrefied for different lengths of time (15 min to 60 min) at a constant temperature. Torrefaction was shown to have positive effects on the fuel characteristics of *Larix kaempferi* C, including improved energy density, storage, and grindability.

**Keywords :** torrefaction, *Larix kaempferi*, calorific value, hydrophobicity, grinding energy

## 1. INTRODUCTION

Currently, growing concerns over fossil fuel emissions and global warming have made searching for fossil fuel alternatives. In addition, the eventual exhaustion of the crude oil supply is another factor that increases the necessity of finding fossil fuel alternatives. Lignocellulosic material is a potential alternative energy source, because it is abundant, renewable, and carbon

neutral (Chheda *et al.* 2007; Stöcker 2008; Na *et al.* 2013). However, the low energy density and storage issues (i.e., contamination by microbes) associated with wood materials are considered limitations to the use of wood biomass as an energy source.

Torrefaction, a mild thermal treatment of woods performed at temperatures below 300°C and under oxygen-free conditions, is regarded as one possible way to overcome the afore-

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mentioned disadvantages (van der Stelt *et al.* 2011; Batidzirai *et al.* 2013; Lee and Lee 2014). The torrefaction process could improve wood products' energy density and hydrophobicity, improving ease of transport, storage, and the potential usefulness of these products. During the torrefaction process, dehydration, dehydroxylation, and decarboxylation occur (Mei *et al.* 2014). Torrefaction causes a transformation of the chemical structure of woods, leading to the decrease of the O/C and H/C ratios in the treated biomass. The result of this is an increase in the wood's energy density (Arias *et al.* 2008; Chew and Doshi 2011; Van der Stelt *et al.* 2011; Mei *et al.* 2014).

Cellulose and hemicelluloses are the main constituents of woods and contain numerous hydroxyl groups that are strongly hydrophilic (Marcovich *et al.* 1998; Ichazo *et al.* 2001). Because the hydroxyl groups are a major factor in the hydrophilicity of woods, removal of the hydroxyl groups in wood via the torrefaction process increases the material's hydrophobic properties (Bourgeois *et al.* 1989; Kim *et al.* 2012; Kobayashi *et al.* 2008). Additionally, the resistance of thermal-treated wood to microbial damage has been reported in previous papers (Kamdem *et al.* 2002; Hokkou *et al.* 2006; Esteves and Pereira 2009; Tripathi *et al.* 2014).

Energy densification could be also achieved by pelletizing wood chips (Li and Liu 2000; Stelt *et al.* 2011). This decreases the cost of both transportation and utilization, since wood pellets have higher energy than wood chips at a same bulk density (Robbins 1982; Stelt *et al.*

2011). However, the grinding which must take place before the pelletizing process procedure requires additional energy for producing fuel pellets. The economic burden of the pelletizing process can be reduced by torrefaction, because less energy is required to grind torrefied wood chips than general wood chips. (Arias *et al.* 2008; Mei *et al.* 2015).

The goal of this study was to evaluate the fuel characteristics of torrefied wood chips, using *Larix kaempferi* C. To achieve this objective, the fuel properties of torrefied wood chips were evaluated for calorific value, energy yield, grindability, and hydrophobicity.

## 2. MATERIALS and METHODS

### 2.1. Raw Material

*Larix kaempferi* C (LAR) was used as the raw material for the torrefaction process. Logs of LAR were purchased from Punglim Co. (Daejeon, Korea). The harvested logs were chipped to two different sizes (10-20 mm and 20-25 mm) using a chipping machine. The chips were screened to regulate chip size, then dried and used in the torrefaction process.

### 2.2. Torrefaction Process

The torrefaction process was carried out at different temperatures (200°C, 220°C, 240°C, 260°C, 280°C, and 300°C) using a pilot scale rotary batch reactor (designed by Drying Engineering Inc., Korea). Precisely 3 kg of

wood chips of LAR was used for each trial of the torrefaction process. The reactor temperature was heated from room temperature to the target temperature over 20 min, after which the target temperature was maintained for 30 min. At 260°C, the residence time was varied (15 min, 30 min, 45 min, and 60 min).

### 2.3. Sample Analysis and Torrefaction Yield

#### 2.3.1. Moisture, chemical composition, and calorific value

The moisture contents of all the samples used were determined by the oven-drying method. The analysis of the chemical composition of the untreated wood samples was performed according to the standard procedure of the American Society for Testing and Materials (ASTM). The calorific values of the samples were determined based on the 1 g of dry weight of each sample and using a Parr 6400 automated bomb calorimeter (Parr, USA). The elemental contents were estimated using Flash EA1112 (Thermo, USA), according to the manufacturer's instruction.

#### 2.3.2. Torrefaction yield

The mass and energy yields of the torrefied samples were based on the dry weight (d) and defined using following equations (1) and (2), respectively.

$$\text{Mass yield } (Y_M) = \frac{\text{Mass (d) of torrefied biomass}}{\text{Mass (d) of raw biomass}} \times 100 (\%) \dots\dots\dots (1)$$

$$\text{Energy yield } (Y_E) = \frac{\text{Calorific value (d) of torrefied biomass}}{\text{Calorific value (d) of raw biomass}} \times 100 (\%) \quad (2)$$

### 2.4. Determination of contact angle

Wood pads manufactured via pressing powdered, untreated, and torrefied wood chips at 41 MPa were used to measure the contact angle, using a Phoenix 300 contact angle measuring instrument (SEO, Korea). Approximately 5 µl of distilled water was dropped onto the surface of the wood pads using a micro-syringe. An image of the dropped water was taken every second for 10 s. The contact angle was obtained at the first second of contact, and this process was repeated 3 times.

### 2.5. Determination of grindability and energy consumption

The energy needed to grind 10 g of untreated and torrefied wood chips for one minute was measured using a commercial grinder with a power consumption measurement apparatus. The size distribution of the pulverized wood particles from the grinding experiments was measured by screening the particles for 20 min using a vibrating sieve device with three different sieves of 60, 40, and 18 mesh.

## 3. RESULTS and DISCUSSION

### 3.1. Torrefaction Characteristics

Changes in elemental composition during the

**Table 1.** Elemental composition and calorific values of untreated and torrefied wood chips

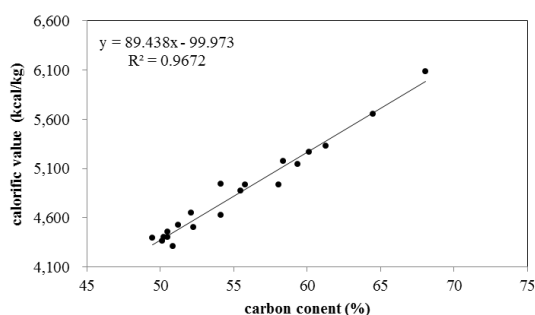
Chip size (mm)	Temp. (°C)	Time (min)	Elemental composition (%)				Calorific value (kcal/kg)
			C	H	N	O <sup>a</sup>	
		Control <sup>b</sup>	49.73 (0.08) <sup>c</sup>	6.69 (0.01)	0.10 (0.01)	43.49 (0.06)	4399.11 (41.89)
10-20	200	30	50.24 (0.08)	6.51 (0.05)	0.09 (0.03)	43.15 (0.10)	4401.59 (14.37)
		220	50.84 (0.08)	6.39 (0.04)	0.14 (0.03)	42.63 (0.08)	4307.85 (29.54)
		240	52.10 (0.04)	6.15 (0.12)	0.05 (0.00)	41.70 (0.16)	4650.6 (28.95)
		260	55.48 (0.07)	6.06 (0.06)	0.10 (0.03)	38.37 (0.09)	4873.92 (3.34)
		280	59.36 (0.31)	5.79 (0.08)	0.08 (0.00)	34.77 (0.35)	5146.8 (13.99)
		300	64.50 (0.38)	5.32 (0.07)	0.13 (0.00)	30.05 (0.33)	5650.93 (19.84)
20-25	200	30	49.45 (0.07)	6.42 (0.02)	0.10 (0.03)	44.04 (0.11)	4392.33 (12.46)
		220	50.16 (0.08)	6.34 (0.04)	0.08 (0.00)	43.42 (0.11)	4364.05 (32.38)
		240	51.21 (0.12)	6.22 (0.04)	0.10 (0.02)	42.47 (0.14)	4529.51 (2.08)
		260	54.12 (0.02)	6.04 (0.01)	0.09 (0.01)	39.76 (0.04)	4943.3 (30.88)
		280	60.14 (0.14)	5.66 (0.05)	0.15 (0.01)	34.05 (0.13)	5264.72 (20.29)
		300	68.07 (0.23)	5.11 (0.03)	0.13 (0.04)	26.69 (0.29)	6083.59 (10.08)
10-20	260	15	52.26 (0.03)	6.27 (0.13)	0.08 (0.00)	41.40 (0.11)	4501.77 (14.65)
		30	55.48 (0.07)	6.06 (0.06)	0.10 (0.03)	38.37 (0.06)	4873.92 (3.34)
		45	55.77 (0.03)	5.98 (0.03)	0.09 (0.02)	38.15 (0.09)	4938.49 (12.69)
		60	58.39 (0.19)	5.91 (0.03)	0.13 (0.04)	35.57 (0.26)	5177.32 (28.47)
20-25	260	15	54.12 (0.02)	6.29 (0.05)	0.13 (0.03)	39.47 (0.11)	4628.78 (11.16)
		30	56.21 (0.02)	6.04 (0.01)	0.09 (0.01)	37.66 (0.03)	4943.3 (30.88)
		45	58.07 (0.05)	5.99 (0.02)	0.12 (0.03)	35.82 (0.04)	4931.99 (10.85)
		60	61.28 (0.04)	5.84 (0.01)	0.16 (0.01)	32.73 (0.05)	5330.37 (22.16)

<sup>a</sup> The oxygen content was calculated by difference

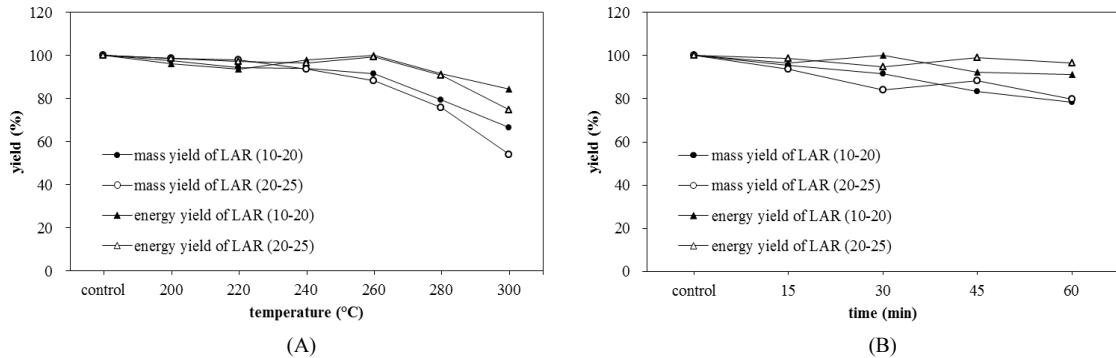
<sup>b</sup> Untreated wood chips

<sup>c</sup> The numbers in parentheses refer to standard deviations

torrefaction process are shown in Table 1. As torrefaction temperature or time increased, the carbon content of the torrefied LAR increased. The increase in carbon content directly contributed to the increased calorific value of the torrefied wood chips. As shown in previous studies (Kim *et al.* 2012; Chin *et al.* 2013), there is a strong correlation between calorific value and carbon content (Fig. 1). The carbon content increased with torrefaction temperatures



**Fig. 1.** Relationship between calorific values and carbon contents of torrefied LAR.



**Fig. 2.** Mass and energy yields of torrefied LAR as a function of temperature (A) and time (B).

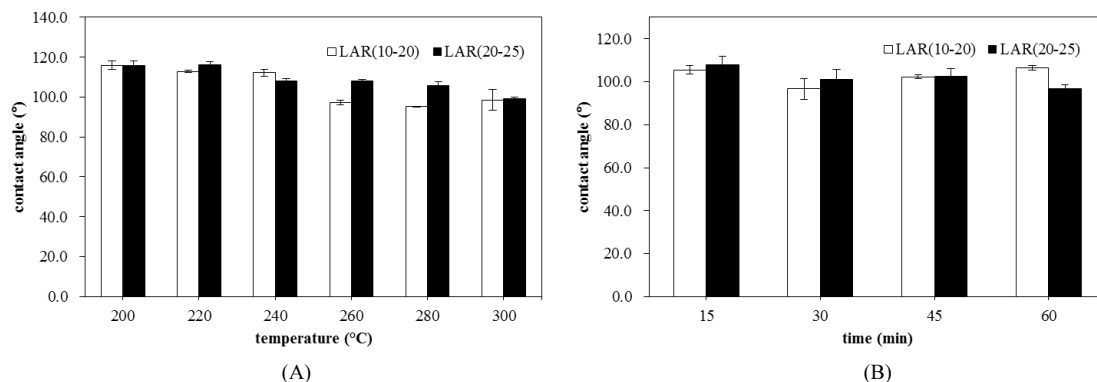
and times because of the decrease in the O/C and H/C ratios caused by the torrefaction process. It was thought that the higher energy contained in the carbon-carbon bond than in C-O or C-H bonds is one of the major factors affecting the molecules' combustion characteristics (Kim *et al.* 2012). Additionally, hydrogen and oxygen content were gradually decreased with time and temperature of treatment of LAR. The behavior of these elemental compositions might be due to the release of volatile compounds such as water and carbon dioxide, both of which are rich in hydrogen and oxygen (Na *et al.* 2013). The nitrogen content of torrefied LAR was nearly constant at a very low level. The calorific value of the wood chips increased significantly due to the torrefaction process, as a function of both torrefaction temperature and time. Under the same treatment conditions, large wood chips showed more severe torrefaction effects than small wood chips. This result might be driven by heat conservation effects occurring in inner part of the large wood chips, caused by the insulative properties of

woods.

Fig. 2 shows the mass and energy yields of torrefied LAR, under different treatment conditions. The yields of torrefied LAR were significantly affected by both torrefaction temperature and reaction time. At a temperature range from 200 to 240°C, the differences in mass and energy yields are negligible. However, a treatment temperature range from 280 to 300°C led to significantly reduced mass and energy yields, as the large increase in the calorific value of the fuel was not enough to make up for the large amount of fuel weight lost (> 30%) during the treatment process. Therefore, these results indicate that thermal treatment at 260°C provides the most positive effects of the torrefaction process, without causing a significant loss in fuel mass.

### 3.2. Hydrophobicity of Torrefied Wood Chips

The hydrophobicity of LAR was evaluated by measuring the contact angles formed by water



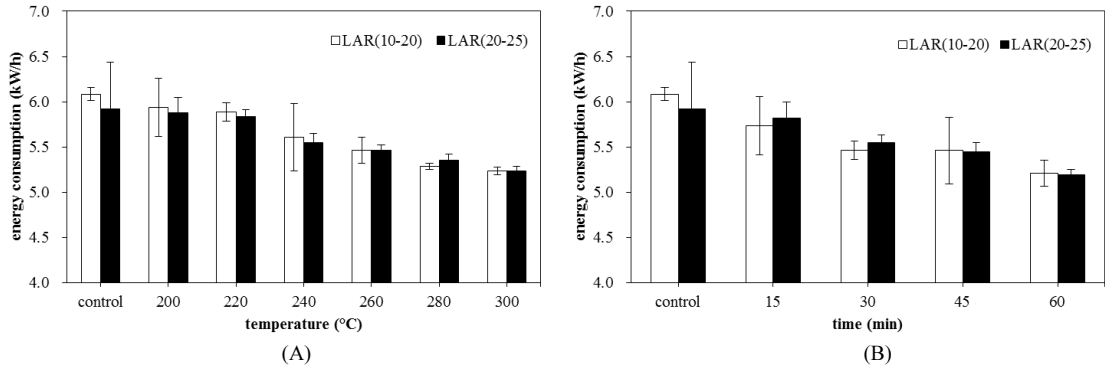
**Fig. 3.** Contact angles of a water droplet on the torrefied LAR, treated by different torrefaction temperature (A) and different residence time (B).

droplets on surface of torrefied LAR. The contact angles ranged from 95.2 to 116.1° (Fig. 3). The contact angle of untreated LAR was not observed, because the hydrophilicity of untreated LAR prevents water droplets from forming the hemispherical shape needed for this measurement. There is no clear correlation between contact angle and torrefaction temperature or time. Although thermal treatment was mild (i.e., low torrefaction temperature or short holding time), the hydrophobicity of LAR was significantly enhanced compare to that of untreated LAR. Similar observations were made in previous studies (Kamdem *et al.* 2002; Pétrissans *et al.* 2003; Weiland and Guyonnet 2003; Hakkou *et al.* 2006). Changes in the surface properties of the wood from hydrophilic to hydrophobic characteristics due to torrefaction can reduce the wetting of woods, and thereby preventing microbial contamination. The results of the measurement of the contact angles of various torrefied LAR samples showed that the torrefaction of LAR can increase its hydro-

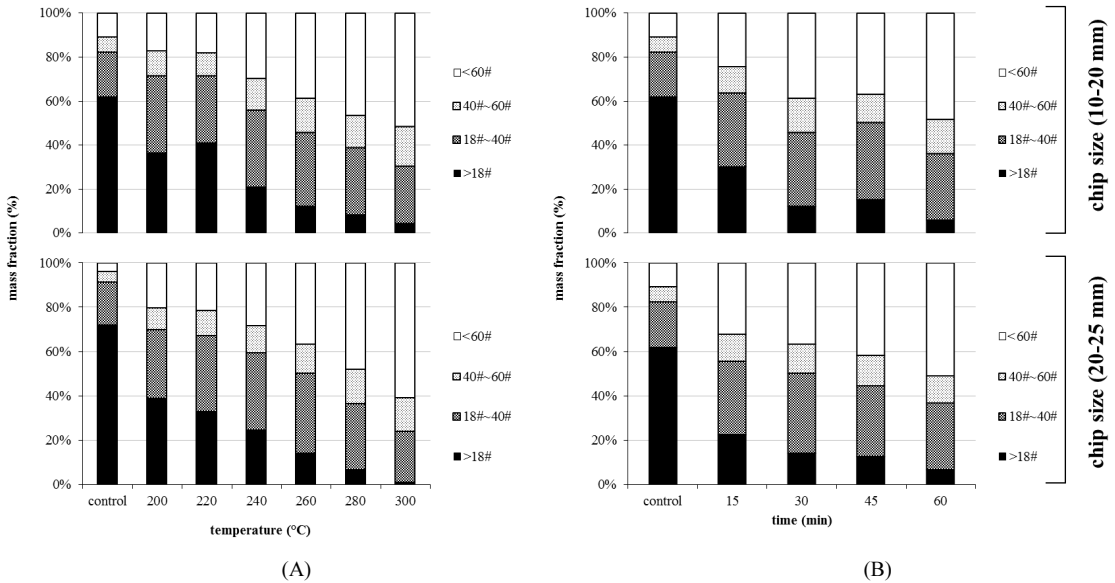
phobicity, which might be advantageous to the long-term storage of torrefied biomass.

### 3.3. Grinding ability and energy consumption

The pelletizing process is generally used to increase the energy density of wood chips. Wood pellets have a uniform shape, which is an advantage in a boiler supply and allows wood pellets to contain a higher calorific value as the same volume of wood chips (Stelt *et al.* 2011). However, higher energy input is required to produce pellets from wood chips, especially during grinding and pelletizing. Energy consumption during the grinding of torrefied LAR is shown in Fig. 4. The required grinding energy was reduced by increasing torrefaction temperature and time. The smallest amount of energy consumed by grinding wood chips came from the wood samples treated at 260°C for 60 min. This is equivalent to a 14.4% and 12.6% reduction in grinding energy from that of un-



**Fig. 4.** Energy consumption during the grinding of torrefied LAR chips treated by different torrefaction temperature (A) and different residence time (B).



**Fig. 5.** Diagram of the particle size distribution of torrefied LAR treated by different torrefaction temperature (A) and different residence time (B).

treated wood, in the case of 10-20 mm and 20-25 mm size chips, respectively. When chips were treated at 300°C for 30 min, the chips with a size of 10-20 mm and 20-25 mm required 14.0% and 11.3% less energy to grind than untreated chips, respectively. The improved

grindability of torrefied LAR might be due to the increase in brittleness of the chips, as well as the breakdown of fibrous compounds during the torrefaction process (Arias *et al.* 2008; Phanphanich and Mani 2011).

The post-grinding distribution of torrefied

LAR particle size within the four size ranges is shown in Fig. 5. According to these results, a larger quantity of small particles (< 40 mesh) was produced when LAR was torrefied at higher temperatures. Almost 5- and 16-fold higher quantity of fine particles (< 60 mesh) were produced by grinding of LAR torrefied at 300°C (size in 10-20 mm and 20-25 mm, respectively). Because the ground particles from untreated larger wood chips contained a smaller quantity of fine particles, wood chips with a size of the 20-25 mm range showed the greatest increase in grinding efficacy due to the torrefaction process. A similar distribution of particles was observed when the LAR chips were torrefied for different time durations at same temperature. Overall, the grindability of torrefied LAR was enhanced by torrefaction, and chips were ground into smaller particles when torrefied at higher temperature or for a longer residence time.

#### 4. CONCLUSION

In this study, the torrefaction process to upgrade fuel characteristics was evaluated. The torrefaction of LAR caused a loss of wood chip mass, but LAR was shown to have a higher energy density because of the increase in calorific value caused by torrefaction. Storage of LAR chips might be improved by the torrefaction process, because torrefied wood chips have hydrophobic properties. Furthermore, the energy consumed by the grinding of torrefied LAR was lower than that required by the grind-

ing of untreated LAR. Thus, the torrefaction process would be advantageous when the torrefied wood chips are used in pelletizing processes. The chip size of LAR did not have a significant effect on fuel characteristics, except on the size distribution of ground wood particles. In light of growing demands for alternative energy, the torrefaction of wood biomass could be a useful method for improving the fuel characteristics of wood.

The torrefied woody biomass has relatively low internal bonding strength and this causes the lower durability of torrefied pellets than wood pellets. Furthermore, it is generally thought that fuel characteristics of final fuel formats such as pellets and briquettes are differed to wood particles and wood chips because their fuel characteristics could be changed during the figuration process. Further studies are needed to enhance the durability of torrefied pellets (i.e., mixing with additives) and evaluate the fuel characteristics of torrefied woody biomass in the form of final products.

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#### REFERENCES

American Society for Testing and Materials,



- Standard test method for ash in biomass. In: Annual book of ASTM standards, ASTM international, West Conshohocken, PA, 2005, ASTM E 1755-01.
- American Society for Testing and Materials, Standard test methods for direct moisture content measurement of wood and wood-base materials. In: Annual book of ASTM standards, ASTM international, West Conshohocken, PA, 2005, ASTM D 4442-07.
- Batidzirai, B., Mignot, A.P.R., Schakel, W.B., Junginger, H.M., Faaij, A.P.C. 2013. Biomass torrefaction technology: Techno-economic status and future prospects. *Energy* 62: 196~214.
- Chen, W.-H. and Kuo, P.-C. 2010. A study on the torrefaction of various biomass materials and its impact on lignocellulosic structure simulated by a thermogravimetry. *Energy*. 35: 2580~2586.
- Chheda, J.N., Huber, G.W., Dumesic, J.A. 2007. Liquid-phase catalytic processing of biomass-derived oxygenated hydrocarbons to fuels and chemicals. *Angewandte Chemie International Edition*, 46(38): 7164~7183.
- Chin, K.L., H'ng, P.S., Go, W.Z., Wong, W.Z., Lim, T.W., Maminski, M., Paridah, M.T., Luqman, A.C. 2013. Optimization of torrefaction conditions for high energy density solid biofuel from oil palm biomass and fast growing species available in Malaysia. *Industrial Crops and Products*. 49: 768~774.
- Eseves, B.M., Pereira, H.M. 2009. Wood modification by heat treatment: a review. *Bioresources*. 4(1): 370~404.
- Hakkou, M., Pétrissans, M., Gérardin, P., Zoulalian, A. 2006. Investigations of the reasons for fungal durability of heat-treated beech wood. *Polymer Degradation and Stability*. 91: 393~397.
- Ichazo, M.N., Albano, C., Gonzalez, J., Perera, R., Candal, M.V. 2001. Polypropylene/wood flour composites: treatments and properties. *Composite structures*, 54(2): 207~214.
- Kamdern, D.P., Pizzi, A., Jermannaud, A. 2002. Durability of heat-treated wood. *Holz als Roh- und Werkstoff*. 60: 1~6.
- Kim, Y.-H., Lee, S.-M., Lee, H.-W., Lee, J.-W. 2012. Physical and chemical characteristics of products from the torrefaction of yellow poplar (*Liriodendron tulipifera*). *Bioresource Technology*. 116: 120~125.
- Lee, S.M., Lee, J.W. 2014. Optimization of biomass torrefaction conditions by the gains and loss method and regression model analysis. *Bioresource Technology*. 172: 438~443.
- Li, Y., Liu, H. 2000. High-pressure densification of wood residues to form an upgraded fuel. *Biomass and Bioenergy*. 19: 177~186.
- Marcovich, N.E., Reboredo, M.M., Aranguren, M.I. 1998. Dependence of the mechanical properties of wood flour-polymer composites on the moisture content. *Journal of Applied Polymer Science*. 68: 2067~2076.
- Mei, Y., Liu, R., Yang, Q., Yang, H., Draper, C., Zhang, S., Chen, H. 2014. Torrefaction of Cedarwood in a pilot scale rotary kiln and the influence of industrial flue gas. *Bioresource Technology*. (in press).
- Na, B.-I., Kim, Y.-H., Lim, W.-S., Lee, S.-M., Lee, H.-W., Lee, J.-W. 2013. Torrefaction of oil palm mesocarp fiber and their effect on pelletizing. *Biomass and Bioenergy*. 52: 159~165.
- Pétrissans, M., Gérardin, P., El Bakali, I., Serraj, M. 2003. Wettability of heat-treated wood. *Holzforschung*. 57(3): 301~307.
- Phanphanich, M., Mani, S. 2011. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource Technology*. 102: 1246~1253.
- Robbins, W.C. 1982. Density of wood chips. *Journal*

- of Forest. 80: 567.
- Stelte, W., Holm, J.K., Sanadi, A.R., Barsberg, S., Ahrenfeldt, J., Henriksen, U.B. 2011. Fuel pellets from biomass: The importance of the pelletizing pressure and its dependency on the processing conditions. Fuel. 90: 3285~3290.
- Stöcker, M. (2008). Biofuels and biomass-to-liquid fuels in the biorefinery: Catalytic conversion of lignocellulosic biomass using porous materials. Angewandte Chemie International Edition, 47(48), 9200~9211.
- Tripathi, S., Pant, H., Kashyap, A.K. 2014. Decay resistance against basidiomycetes fungi of heat-treated *Pinus roxburghii* and *Mangifera indica* wood. Journal of Tropical Forest Science. 26(2): 203~207.
- van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J. 2011. Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass and Bioenergy 35: 3748~3762.
- Weiland, J.J., Guyonnet, R. 2003. Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy. Holz als Roh- und Werkstoff. 61: 216~220.