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Changes in the Combustion Characteristics of Living Quercus Mongolica Leaves with Altitude Variation

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In this study, combustion tests were conducted on living *Q. mongolica* leaves to compare their combustion characteristics at different altitudes. Leaf moisture content was measured and combustion characteristics were then studied using an ignition temperature tester, a cone calorimeter, and a smoke density chamber. The samples contained 117–145% moisture. The temperature of non–flame ignition was 275–308 °C and did not vary with altitude. Samples from 1,300 m and 1,500 m ignited more quickly than the others, but went out after 2 and 4 seconds, respectively. Heat release increased and reached its peak at 1,100 m, thereafter decreasing. Smoke release decreased and smoke density increased in proportion to altitude. The mean release density of CO rose gradually with increasing altitude while that of CO_2 increased from 1,200 m.

INTRODUCTION

The gravity of forest fires are evaluated by representations of individual or synthetic dangerousness, which consist of several factors including topography, atmospheric phenomena, and fuel type, all of which affect the mechanisms of forest fire spread (Kim *et al*., 2006). Fuel, one of the elements affecting the mechanisms of forest fire spread, brings about various patterns and shapes of fire according to its kind and form. This leads to differences in complex combustion in terms of, e.g., ignition, smoke release, the rapidity of heat release, toxicity, and the amount of heat released (Davis *et al*., 1959). Hence, to predict fire intensity and fuel movement, one must survey the types and shape of fuel in a forest and analyze the combustion characteristics of flammable fuel. Furthermore, to confirm combustion characteristics systematically, research into the combustion characteristics of fuel according to the forest physiognomy of each region and the study of atmospheric phenomena and topographical peculiarities should be performed simultaneously.

Currently, a variety of disaster prevention measures are aimed at local and international forests. The system for rating forest fire dangerousness marks hazardous sections with four indices, which are helpful for the establishment of fire prevention projects. These indices are the artificial forest fire occurrence index, forest fire occurrence caused by lightning index, combustion index, and combustion amount index (Lee, 2004). To predict the level of dangerousness of surface fire fuel, some research on the quantification of forest fire intensity using the amount of heat per unit area has been undertaken.

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Recently, studies on the combustion characteristics of flammable material in a forest have been conducted in Korea (Kim *et al*., 1995; Kim *et al*., 1999; Park *et al*., 2007). Predicting the dangerousness of a forest fire to flammable material is difficult, as researchers and equipment cannot easily access and test the site of fires, and thus gathering data from indoor experiments is common (Jung *et al*., 2002; KS F 2271, 1998). However, locally adverse circumstances can prevent researchers from identifying combustion patterns through experiments, leading to incomprehensive studies. To examine systemic combustion mechanisms, various experiments based on chemical methods are needed.

A geographical feature of Korea is that the northeastern mountainous district has high altitudes, while the northwestern district contains extensive, low, gently rolling hills. Accordingly, vegetation distribution and structure varies according to altitude, and tree species and forest types are noticeably different between the two regions (Gangwon Provincial Police Agency, 2002). The forest zone of Korea is divided into tropical forest, temperate zone forest, and frozen zone forest. The representative species of temperate zone forests in Korea include *Styrax japonica* Sieb. et Zucc., *Quercus serrata* Thunb., *Quercus mongolica* Fischer, *Juniperus chinensis* Linn., *Abies holophylla* Maximowicz, *Betula davurica* Pall., and *Pinus densiflora* Sieb. et Zucc. (Yim, 2007).

In this study, tests on the combustion characteristics of fuel from various altitudes were conducted to compare the fire characteristics of forest fuels. Living *Q. mongolica* leaves were used as test fuel. The purpose of this research was to collect basic data to establish criteria for predicting the movement of forest fires by analyzing characteristics of ignition, fire, and smoke release.

MATERIALS AND METHODS

1. Site selection

1.1. Study site and fuel

Mt. Taeback (altitude, 1,567 m), in Gangwon Province, was chosen as the study site for this research, as it has the topographic characteristics and vegetation resources of the east coast area, where large–scale forest fires most frequently occur in Korea. Living leaves of *Q. mongolica*, which is the dominant oak in temperate zone forests, were selected as the test fuel, as this species occurs across a range of altitudes on the mountain. Fuel sampling was conducted by picking up seven samples on hiking trails every 100 m from altitudes of 900 to 1,500 m. Living leaves were chosen as fuel to use the fuel type that would be naturally available during a forest fire.

1.2. Measuring moisture content

Before combustion characteristic tests were conducted, the moisture content of the sample fuel was measured. Moisture content was measured using formula (1) according to ASTM D2016 (American Society for Testing and Material) (Kim *et al.*, 2004; Shim *et al.*, 1994). A 200–g sample was dried in a 103 °C oven for 24 hours, and was then measured until it reached constant mass. The mean value of three measured values was used as the outcome value. Samples were collected in October, after 5 consecutive fine days. MC (moisture content) is the moisture content ratio [%], W represents the weight of samples before drying [g], and W0 is the weight of dried samples.

$$MC\ (\%) = \frac{W - W_0}{W_0} \times 100\ (\%) \qquad (1)$$

1.3. Combustion characteristic tests

To test the combustion characteristics of living *Q. mongolica* leaves with altitude variation, tests on the characteristics of ignition, fire, and smoke release were conducted. To analyze the characteristics of ignition, ignition temperature (IT), time to ignition (TTI) and time to flameout (TTF) were measured. For an analysis of fire characteristics, total heat release (THR) and mean heat release rate (mean HRR) were used, and for the characteristics of smoke release, total smoke release (TSR), maximum smoke density (max. Ds), and smoke temperature (Ts) were measured. The mean release densities of the combustion products CO and CO_2 were also analyzed.

2. Methods

2.1. Analysis of ignition characteristics

To analyze ignition characteristics, non–flame IT was measured using an IT chamber (model number KRS–RG–9000; Kuramochi Co., Japan; Hong *et al.*, 1992). The time for flash ignition, when fuel was exposed to radiation, was recorded using a cone calorimeter. Flame close time, namely, the time when the fire was extinguished naturally, was measured and after–flame time was analyzed simultaneously. The presence or absence of a flame at flash ignition was recorded, as judged by the naked eye.

2.2. Analysis of fire characteristics

To examine fire characteristics, a dual cone calorimeter chamber (ISO 5660–1, 2002) of FTT Co., England was used to analyze the mean HRR. The experiment ended when the sample stopped decreasing in weight, and this value was chosen as the output value. The mean value of three replicates was used as the outcome value. The THR was calculated based on the accumulated value by integrating the heat release rate, represented by a function of time, per its sample's surface area. The mean HRR was calculated by dividing the THR by the given amount of time. The experimental conditions are presented in Table 1.

2.3. Analysis of smoke release characteristics

To analyze the characteristics of smoke release, a smoke density chamber (ASTM E 662, 2003) and cone calorimeter (FTT Co.) were used. TSR and Ts were measured with the cone calorimeter, and smoke density was analyzed using the smoke density chamber. Since TSR measured by the cone calorimeter is the total smoke occurrence per unit area according to ISO 5660–2 (ISO 5660–2, 2002), and as smoke occurs in proportion to area, a standard value related to the area was used.

The total smoke occurrence rate (m^2) was the value integrated by the time of smoke release (m^2/s) in the related section. Ts was measured using a thermocouple when the smoke had passed through a 0.5–mW helium–neon laser in a duct. For the measurement of smoke density, a smoke density chamber was used, applying a vertical test of non–flaming. The mean value of three replicates was used as the outcome value. Experimental conditions are presented in Table 1.

RESULTS AND DISCUSSION

To compare the combustion characteristics of fuel from varying altitudes, combustion tests were conducted on living *Q. mongolica* leaves that were collected at 100–m altitude intervals on Mr. Taeback, Gangwon Province, Korea. The results were as follows.

Table 1. Experimental conditions for the smoke density chamber and cone calorimeter

Items	Cone calorimeter	Smoke density chamber
Size (mm)	100×100	75×75
Weight (g)	50	10
Heat flux (kW/m^2)	50	25
Test time (s)	the time until there is no more weight decrease	1,200
Material condition	raw	raw

1. Moisture content characteristics

Fig. 1 shows the moisture content curve of living *Q. mongolica* leaves with altitude variation. Leaves contained 117–145% moisture at various altitudes. Moisture contents at 1,300 m and 1,400 m were lower than at other altitudes. Leaves had moisture contents of 120.44, 130.71, 131.88, 139.90, 117.35, 116.45, and 144.72% from altitudes of 900, 1,000, 1,100, 1,200, 1,300, 1,400, and 1,500 m, respectively.

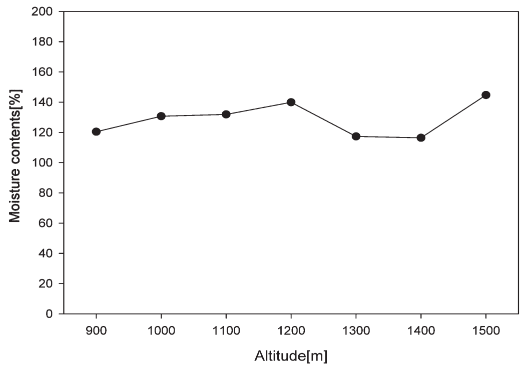

Fig. 1. Moisture content percentages of living *Q. mongolica* leaves from various altitudes.

2. Ignition characteristics

Table 2 shows the ignition characteristics of living *Q. mongolica* leaves from various altitudes. The ITs in Table 2 indicate the non–flame IT temperature, which varied little from 275 to 308 °C. Samples from 1,100 m and 1,300 m had low ITs. When recording the TTI and TTF, the cone calorimeter used in this study measured only the flame ignition time, not non–flame ignition. Flame ignition time was recorded for all altitudes except 1,200 m.

Although the flame ignition of the 1,200 m sample was not observed, the high heat release shown in Table 3 and the high TSR shown in Fig. 4 indicate that non–flame ignition occurred. Samples from 1,300 m and 1,500 m ignited faster than the other samples, but the flames faded away after 2 and 4 seconds, respectively. Conversely, the sample from 1,400 m had an ignition time of 59 seconds, but its flame was maintained for the longest of all samples.

3. Fire characteristics

Fig. 2 shows the curve of THR with altitude variation, and Fig. 3 shows the curve of the mean HRR. THR was 30–62 MJ/m^2 and mean HRR was 12–33 kW/m^2. From 900 to 1,100 m, heat release increased with altitude, with

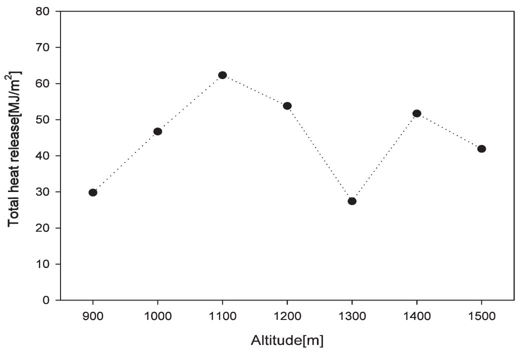

Fig. 2. Total heat release of living *Q. mongolica* leaves from various altitudes.

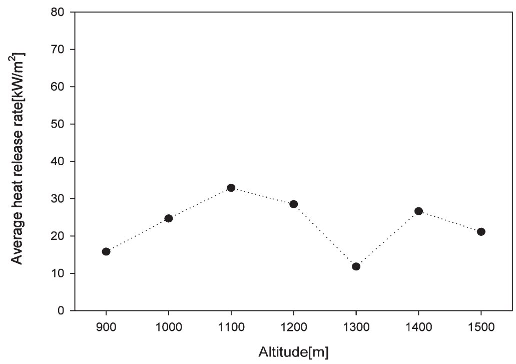

Fig. 3. Heat release rate of living *Q. mongolica* leaves from various altitudes.

Table 2. Ignition characteristics of living *Q. mongolica* leaves from various altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Time to ignition (s)	39	48	57	not recorded	14	59	25
Time to flameout (s)	50	50	62	not recorded	16	75	29
Ignition temperature (˚C)	280	290	275	299	278	306	308

Table 3. Flame spread characteristics of living *Q. mongolica* leaves from various altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Average HRR (kW/m^2)	15.77	24.67	32.87	28.49	11.78	26.62	21.11
Total heat release (MJ/m^2)	29.8	46.7	62.3	53.8	27.4	51.7	41.9

measurements of 15.77 MJ/m², 24.67 MJ/m², and 32.87 MJ/m², respectively. However, from 1,100 m, the heat release decreased with altitude increase to 21.11 MJ/m². Heat release was highest at approximately 1,100–1,200 m. The outcome values are presented in Table 3.

4. Smoke release

4.1. Total smoke release, maximum smoke density, and smoke temperature

Fig. 4 shows the TSR curve for 50–g samples and Fig. 5 presents the maximum smoke density curve. The highest TSR was 220.02 m²/m² from the 900 m sample, which was 2.5 times higher than the 87.50 m²/m² released by the 1,000 m sample. Maximum smoke density was lowest in the 900 m sample, at 51.56 Ds, increasing to 65.47 Ds in the 1,200 m sample and thereafter increasing with altitude to 91.38 Ds.

Hence, high altitude forest fires will release more smoke, greatly reducing visibility, as compared to fires at low altitudes. Fig. 6 shows the peak Tss of combustion. The range of maximum Ts was 63–65 °C, with no variation according to altitude. Outcome values are presented in Table 4.

4.2. CO and CO_2

Fig. 7 shows the mean release densities of CO and CO_2 for 50 g of living *Q. mongolica* leaves with altitude variation. The mean release density of CO rose gradually, which suggests that as the altitude increases, smoldering occurs, rather than complete combustion, yielding more CO. The mean release density of CO_2 shows no consistent variation with altitude, but density increases with increasing altitude from 1,200 m.

The combustion products of CO and CO_2 were produced at higher temperatures, after being pyrolyzed from cellulose, the main component of the leaves, into organic aldehyde or organic acid (Lee, 2005). Smoke and combustion products, yielded from fuel combustion, change

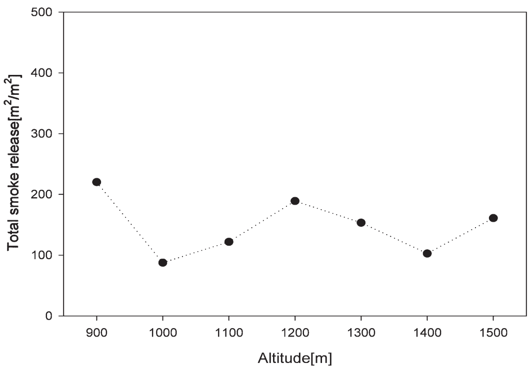

Fig. 4. Total smoke release of living *Q. mongolica* leaves from various altitudes.

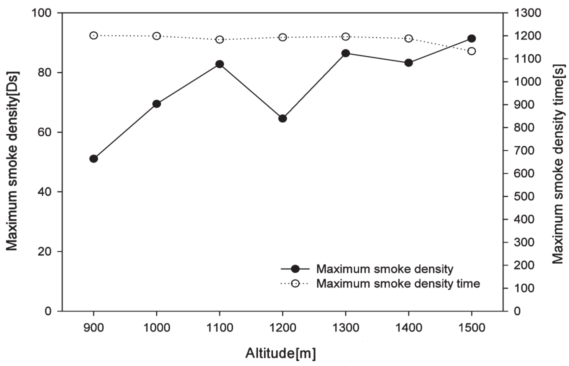

Fig. 5. Smoke density of living *Q. mongolica* leaves from various altitudes.

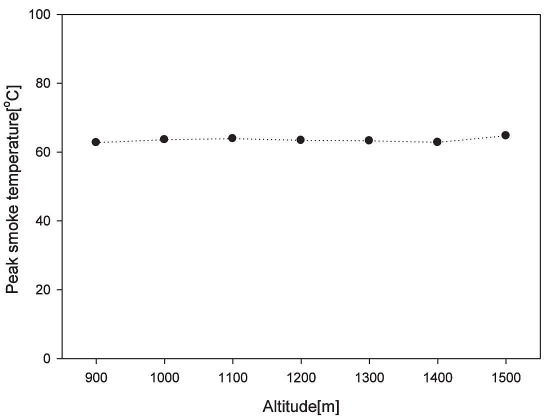

Fig. 6. Smoke temperature of living *Q. mongolica* leaves from various altitudes.

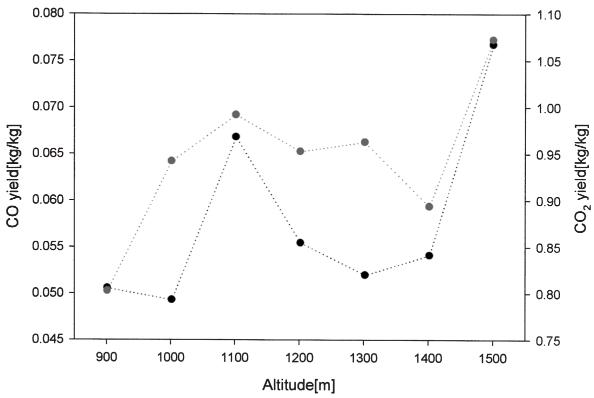

Fig. 7. CO and CO_2 yields of living *Q. mongolica* leaves from various altitudes.

Table 4. Smoke release characteristics of living *Q. mongolica* leaves from various altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Total smoke release (m²/m²)	220.02	87.5	121.9	189.1	153.3	102.6	160.89
Peak smoke temp. (°C)	61.23	61.42	61.07	62.01	63.46	63.8	63.89
Max. smoke density (Ds)	51.06	69.48	82.8	64.57	86.45	83.25	91.38
Max. ds time	1,201	1,199	1,183	1,193	1,196	1,188	1,133

Table 5. Concentrations of combustion gases for living *Q. mongolica* leaves from various altitudes

Items	Altitudes (m)						
	900	1,000	1,100	1,200	1,300	1,400	1,500
Average CO yields	0.0651	0.0568	0.0785	0.0644	0.0906	0.1226	0.0891
Average CO_2 yields	1.06	0.99	1.23	0.93	1.03	1.16	1.18

according to aspects of fire progress. Accordingly, the density and toxicity of smoke must be considered apart from other factors (Lee, 1993). Experimental conditions are presented in Table 5.

CONCLUSIONS

In this study, a series of experiments were conducted on living leaves of *Q. mongolica* to compare the combustion characteristics of fuel with varying altitude. The conclusions are as follows.

1) Moisture content measurement showed that living *Q. mongolica* leaves from Mt. Taeback had moisture contents of 117–145%. Samples from altitudes of 900, 1,000, 1,100, 1,200, 1,300, 1,400, and 1,500 m had moisture contents of 120.44, 130.71, 131.88, 139.90, 117.35, 116.45, and 144.72%, respectively. Samples from 1,300 m and 1,400 m had slightly lower moisture contents.
2) Ignition characteristics varied little between altitudes, with non–flame temperatures of 275–308°C. Samples from 1,100 m and 1,300 m had relatively low non–flame temperatures. TTI tests showed that 1,300 m and 1,500 m samples ignited faster than the other samples, but the flames faded after 2 and 4 seconds, respectively. Conversely, the 1,400 m sample had a TTI of 59 seconds, but maintained a flame for the longest of all samples. Although flame ignition of the 1,200 m sample was not observed, the high heat release and TSR indicate that non–flame ignition occurred.
3) Fire characteristic tests showed that THR was 30–62 MJ/m^2, and the mean HRR was 12–33 kW/m^2. Up to 1,100 m, heat release increased with altitude to 32.87 MJ/m^2. However, above 1,100 m, heat release decreased to 2.11 MJ/m^2. The highest heat releases were recorded for samples from 1,100 m and 1,200 m.
4) Smoke characteristic tests showed that the TSR was highest at 900 m (220.02 m^2/m^2), which was 2.5 times more than the total smoke released from the 1,000 m sample (87.50 m^2/m^2). Maximum smoke density was lowest at 900 m (51.06 Ds) and increased with altitude to 91.38 Ds, which means that more smoke was released at the start of combustion with increased altitude.
5) Tests of the release densities of combustion products CO and CO_2 showed that the mean release density of CO rose with increasing altitude, while the density of CO_2 rose from 1,200 m with increasing altitude.

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