

# Evaluation of the combustion characteristics of railroad waste using a cone calorimeter

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**Abstract:** For this study, we categorized waste from railroad operation into seven types; i.e., wood, vinyl, fiber, Styrofoam, food, paper and plastic. We then performed a combustion test using a cone calorimeter that is used widely for evaluating the combustion properties of combustible materials, to evaluate the heat release rate, smoke production rate, carbon monoxide production, carbon dioxide production and mass loss rate during biomass combustion.

**Keywords:** Railroad Waste, Cone Calorimeter, Combustion, CO<sub>2</sub>, Heat Release

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## 1. Introduction

As the Kyoto Protocol came into effect in February 2005, Korea, which is ranked no. 1 in terms of increases in the rate of greenhouse gas emissions, will not be exempted from their obligation to reduce greenhouse gases. Because countries have committed to the UN Framework Convention on Climate Change (UNFCCC) to reduce their emissions, high-energy-consumption and pollution-generating industries are expected to go into decline because of the cost of reducing greenhouse gas emissions and increased production costs (UNFCCC, 2003; Ministry of Environment, 2001). The particulate matter generated when incinerating biomass is one of the causes of global warming; indeed, more particulate matter is emitted by incinerating biomass than by automobiles or industrial facilities (Bernard, 2002). Carbon dioxide comprises ~60% of the total greenhouse gases emitted by humankind. Carbon dioxide is generated mostly by the combustion, extraction, processing and transport of fossil fuels such as coal, oil and natural gas, which are used in industrial activities. Approximately 80–85% of all carbon dioxide generated by human activity is through the use and burning of fossil fuels (Bhattacharya *et al.*, 1999).

Measures of reducing the impact of railroads on the environment and promoting more environmentally friendly railroads is urgently needed. Although various studies have reported that the railroad is more environmentally friendly than other transportation means, it places a significant burden on the already devastated global environment

through atmospheric, water and soil pollution, noise pollution, vibration and waste generation. As such, a suitable response is needed (Korea Environment Institute, 1004). The waste generated by railroad operations includes waste oil, resin, and filters generated during maintenance of the engines, passenger cars, freight cars, and electric trains by the workshops and car offices as well as the paper, cans, and plastics generated by mostly passenger cars and stations. As the amount of waste generated by a railroad operation varies greatly, the statistics differ. However, based on the waste generation and handling costs, 10,530 tons/year were generated by railroad operations in Korea. Of these, 1,038 tons/year were designated waste, 4,592 tons/year were business sites' waste, 717 tons/year were passenger car waste, and 1,869 tons/year were station waste (Korea Railroad Research Institute, 2005).

We categorized the waste from railroad operation into seven types; i.e., wood, vinyl, fiber, Styrofoam, food, paper and plastic. We then performed a combustion test using a cone calorimeter, which is used widely for evaluating the combustion properties of combustible materials, to evaluate the heat release rate, smoke production rate, carbon monoxide production, carbon dioxide production, and mass loss rate during combustion of the biomass. This follows the 'Study of the Combustion Properties of Biomass using a Cone Calorimeter (I)' (Park *et al.*, 2005), which reported the test results of several items of various possible sources of global warming gas emission. We plan to test more materials and determine how these materials contribute to local or global atmospheric environmental changes and

temperature increases.

## 2. Materials and Methods

Table 1 summarizes the general trends of previous studies on biomass combustion properties. Those studies report that biomass is currently used as fuel in many countries, most of which is illegally incinerated. As the

exhaust gas from illegal incineration is mostly discharged without treatment, a considerable amount of global warming gases are allowed to escape into the atmosphere. Many studies of the impact of illegal incineration of biomass are ongoing. Most of these are targeted at wood and fossil fuels and report great differences in global warming gas emissions according to the combustion method used.

*Table 1. Summary of the burning of biomass in a literature review.*

Sample	CO (kg/kg)	CO <sub>2</sub> (kg/kg)	NO <sub>x</sub> (g/kg)	SO <sub>2</sub> (g/kg)	Reference
<i>Wood chip</i>					
50×50×200	0.0259	1.590	0.112		Bhattacharya <i>et al.</i> (2002a)
50×50×50	0.0259	1.597	0.115		Bhattacharya <i>et al.</i> (2002a)
25×25×50	0.0174	1.605	0.213		Bhattacharya <i>et al.</i> (2002a)
<i>Biofuel</i>					
wood	0.0325	0.900	1.500		Kituyi <i>et al.</i> (2001)
wood	0.0002	0.016	0.0001		Bhattacharya <i>et al.</i> (2002b)
charcoal	0.005	0.080	0.140		Kituyi <i>et al.</i> (2001)
charcoal	0.155	2.576	0.0004		Bhattacharya <i>et al.</i> (2002b)
<i>Agricultural residues</i>					
bagasse	0.046	1.266	1.74	0.29	NISTEP (1991)
straw	0.075	1.250			ADB and WECS (1994)
grass	0.045	0.322	2.4		Kannan <i>et al.</i> (2004)
leaves	0.071	1.069	3.0		Kannan <i>et al.</i> (2004)
twigs	0.072	0.889	4.3		Kannan <i>et al.</i> (2004)
ricehusk	0.027-0.052	0.934-1.105			Bahadur (1997)
cone	0.049				Braunstein (1981)
sorghum	0.035				Braunstein (1981)
oats	0.062				Braunstein (1981)
wheat	0.049-0.058				Braunstein (1981)
coconut	0.110				Smith <i>et al.</i> (1987)
sugar-cane				3.18	Braunstein (1981)
dung	0.050	1.060	0.7	6.0	NISTEP (1993)
<i>Pesticide</i>					
cone(50kW/m <sup>2</sup> ) <sup>(1)</sup>	0.027	0.37	14.0	560	Kakko (1995)
cone(25kW/m <sup>2</sup> ) <sup>(2)</sup>	0.026	0.60	4.50	510	Kakko (1995)

Note 1) 50 kW/ m<sup>2</sup>: 782°C. 2) 25 kW/ m<sup>2</sup>: 670°C.

A cone calorimeter is a device used to evaluate the combustion properties of materials. The variables of the biomass combustion properties are described below (Cho and Han, 2004). Time to ignition (TTI, seconds) is the time until the fire is flared, and the heat release rate (HRR, kW/m<sup>2</sup>) is the amount of heat generated per unit area, as shown in Equation (1).

$$\bar{Q}(t) = (\Delta h_c / r_0)(1.10) C \sqrt{\frac{\Delta P}{T_s}} \cdot \frac{X_{O_2}^0 - X_{O_2}}{1.105 - 1.5X_{O_2}} \quad (1)$$

$$\bar{Q}_A(t) = \bar{Q}(t) / A_s$$

Here,  $\bar{Q}$  is heat release (kW) while  $A_s$  is the initial exposed area of the sample. The peak heat release (pkHRR, kW/m<sup>2</sup>) is the heat released from the ignition to the time of peak heat release,  $t_{p}$ (s). The average heat release rate  $\bar{Q}_{60}$  (kW/m<sup>2</sup>) is calculated using Equation (2).

$$\bar{Q}_{60} = \frac{1}{60} \int_{TTI}^{TTI+60} Q(t) dt \quad (2)$$

The average heat release rate from the ignition to 180 s,  $\bar{Q}_{180}$  (kW/m<sup>2</sup>), is calculated using Equation (3).

$$\bar{Q}_{180} = \frac{1}{180} \int_{TTI}^{TTI+180} Q(t) dt \quad (3)$$

THR (total heat release, MJ/m<sup>2</sup>) is calculated using Equation (4).

$$THR = \int_0^{\infty} Q(t) dt \quad (4)$$

$m_L$  (mass loss, %) is calculated using Equation (5).

$$\dot{m}_{A,10-90} = \frac{m_{10} - m_{90}}{t_{90} - t_{10}} \cdot \frac{1}{A_s} \quad (5)$$

$$\text{Here, } \Delta m = m_s - m_r \quad m_{10} = m_s - 0.1\Delta m$$

$$m_{90} = m_s - 0.9\Delta m \quad \Delta H_c$$

To calculate the effective heat of combustion (MJ/kg) in Equation (6),  $m_s$  is the mass of the sample before the test and  $m_r$  is the mass of the sample after the test.

$$\Delta H_c = \frac{\sum \bar{Q}(t) dt}{m_s - m_r} \quad (6)$$

Total smoke released (TSR,  $m^2/s$ ) can be calculated by integrating the smoke release rate ( $S_R$ ) with time.

$$TSR = \int_0^{\infty} S_R dt \quad (7)$$

CO and CO<sub>2</sub> generation (kg/kg) is related to the mass loss of the sample and measured using non-dispersive infrared (NDIR) built into the cone calorimeter.

This study used the waste from a railroad operation as the test sample. The waste was categorized into seven types; i.e., wood, vinyl, fiber, styrofoam, food, paper, and plastic. Railroad waste is items such as those generated from cars after an operation, and is mostly illegally incinerated. Samples were collected from the waste depot, which stocks the waste for later treatment. The samples were ground

using a grinder (TP-6792, Tefal) to 5 mm or smaller in size. To minimize the impact of moisture, they were dried in a drying machine at 105°C for 60 min (Bhattacharya *et al.*, 2002a). To evaluate the change in combustion properties by the elements, each sample was analyzed in terms of its elemental composition using an Automatic Elemental Analyzer (EA 1110, CE Instruments).

The result is shown in Table 2. The moisture content (%) was higher in wood, paper, and food, whereas fiber contained less moisture. Bhattacharya *et al.* (2002a) reported that moisture content significantly affects the generation of CO, CO<sub>2</sub>, and NO<sub>x</sub> when incinerating biomass. The ash contents of vinyl and fiber were 0%; the highest was in paper (45.2%). As such, the vinyl and fiber contained the highest combustible contents. Here, ash content does not represent the value after incineration in the electric furnace but the amount of ash directly generated when the sample is burnt at a 40 kW in a cone calorimeter. The carbon content is closely related to the CO and CO<sub>2</sub> levels generated during combustion of the biomass. The carbon content was 43.8–49.0% and showed a considerable range (36.64–85.97%) among the materials.

Table 2. Elemental analysis of the railroad waste.

Sample	(wt.%)						
	Moisture	Ash	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen
Wood	35.7	1.1	45.47	5.46	5.74	0.05	43.42
Vinyl	15.4	0.0	77.75	11.88	1.03	0.08	10.77
Fiber	7.7	0.0	43.62	3.18	10.38	0.06	47.63
Styrofoam	28.6	1.2	85.97	6.29	3.91	0.10	4.15
Food	35.7	15.5	41.57	6.38	3.28	0.06	43.98
Paper	45.2	39.4	36.64	2.58	7.56	0.10	39.30
Plastic	12.5	11.0	42.39	4.46	3.63	0.16	7.39

We measured CO and CO<sub>2</sub> generation, the heat release rate, and the smoke production rate simultaneously using a cone calorimeter (dual type) (FTT, UK). The test was performed in accordance with the procedure in ISO 5660 Parts 1 and 2. Figure 1 shows the cone calorimeter used in the test. The cone calorimeter is a bench-scale oxygen depletion calorimeter developed by Dr. Vytenis Babrauskas at the National Institute of Standards and Technology. Its name is derived from the cone-shaped heater with the top cut off. It has dimensions of 100 × 100 × 36 mm and is capable of releasing radiant heat of up to 100 kW/m<sup>2</sup> (Babrauskas, 1984). The system consists of a cone-shaped radiant electric heater, sample holder, spark igniter, heat flux meter to measure the heat, burner to measure the methane heat, data acquisition and analysis system, and an NDIR analyzer to measure CO and CO<sub>2</sub>. As mentioned above, the radiant electric heater is shaped like a cone with the top cut off and can generate a radiant heat of up to 100 kW/m<sup>2</sup> with a ratio of 5,000 W at 230 V. It supports both horizontal and vertical tests.

To control the temperature, 3-k type thermocouples and

30 item PID temperature controllers are used. The exhaust system is fabricated from stainless steel and consists of a hood, gas sampling ring probe, exhaust fan (minimum 0.1 g/s resolution and 0–50 g/s flow control), and an orifice plate flow meter (thermocouple and differential pressure transducer). The system can perform more than 10 international standard tests, including ISO 5660, ASTM E 1354, ASTM E 1474, ASTM E 1740, ASTM F 1550, ASTM D 5485, ASTM D 6113, NFPA 264, CAN ULC 135, and BS 476 Part 15.

The test used a 100 × 100 × 36-mm sample holder to fix the sample. The same sample holder and grid were used for all samples. The discharge flow rate was fixed to 24 L/s and the spark igniter was used to ignite the pyrolysis gas. To maintain the equipment at the optimum condition for the test, the following procedure was performed. An uninterruptible power system was connected to supply a known voltage to the cone calorimeter. To stabilize the analyzer, the smoke and O<sub>2</sub>, CO, and CO<sub>2</sub> gas analyzer was switched on 2 h before the test. The gas analyzer was calibrated using N<sub>2</sub>, CO, and CO<sub>2</sub> standard gases, and the

electronic scale inside was calibrated at the same time. The laser used for smoke measurement was calibrated using the calibration lens. To obtain reliable data, the filter through which the exhaust gas passes was replaced after each test. Methane gas was used to calibrate heat release for temperature measurement. The C factor was maintained at  $0.04 \pm 0.002$ . Finally, the temperature of the cone was increased to 25 kW using the heat flux meter. After calibration, the prepared sample holder was placed on the electronic scale, the safety glass was lowered, and the test was performed. To conduct the test, the igniter was started simultaneously with sample insertion and removed when the flame flared to the sample. After sample combustion, data were collected for at least 120 s, and the test was completed.

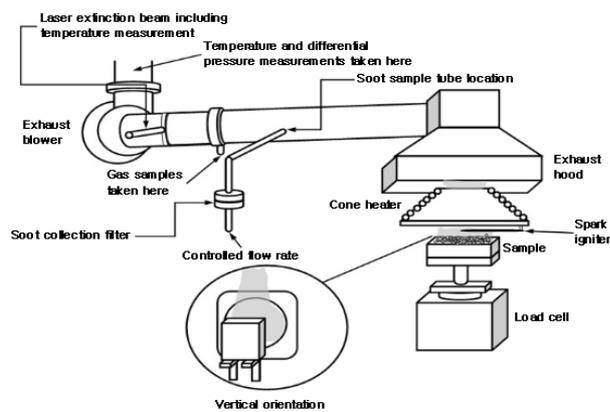


Fig 1. Schematic diagram of the cone-calorimeter used in this study.

### 3. Results and Discussion

Table 3 summarizes the results of testing the seven railroad waste types; i.e., wood, vinyl, fiber, styrofoam, food, paper, and plastic, using the cone calorimeter. Here, TTI is the time between the test start and flame ignition, as recorded by visual inspection of the tester. The result of combusting four samples at 50 kW heat flux indicated that

the ignition time was 3–42 s with the fiber and paper, indicating a fast TTI time; in contrast, the plastic showed the longest time to reach TTI. The peak heat-generation rate (pkHRR) differed somewhat among samples. The different samples also required a wide range of times to reach pkHRR ( $t_{ip}$ ). There was little correlation between pkHRR and the time to reach pkHRR.

Figure 2 shows the heat released during incineration of railroad waste. The initial heat released was in the order of polystyrene foam > vinyl > wood > plastic > fiber > paper. The heat released by the Styrofoam and vinyl was significantly higher than by the other types of waste. The reason for this is suggested by the elemental composition analysis (Table 2). The carbon content of the waste other than Styrofoam and vinyl were almost 30–40 wt%, while those of Styrofoam and vinyl were 85.97 and 77.75 wt%, respectively. In other words, the elemental analysis indicates that Styrofoam and vinyl contained more carbon, which is considered the source of heat, than the other sample types. A comparison of heat generated by the five sample types indicated a correlation between carbon content and heat released. Here, the heat released was calculated by measuring the amount of oxygen consumed during combustion of the biomass. It was assumed that 13 MJ heat is generated by 1 kg of oxygen during combustion (KS F ISO 5660-1). Table 3 shows the heat released per unit time during incineration of the railroad waste and the total heat released.

Total heat released (THR) is the accumulated heat released during biomass combustion. There were considerable differences in THR among the sample types. It should be noted that the THR of food was similar to that of Styrofoam. Although the pkHRR was the lowest, the heat released increased steadily. The THR of Styrofoam (which exhibited a higher initial heat release) was 53.0 MJ/m<sup>2</sup>, while that of food was 54.6 MJ/m<sup>2</sup>, the highest of any waste type.

Table 3. Combustion characteristics of the railroad waste.

Parameter	Materials						
	Wood	Vinyl	Fiber	Styrofoam	Food	Paper	Plastic
<i>Thermal data</i>							
TTI (s) <sup>1)</sup>	8	29	3	29	13	5	42
pkHRR (kW/m <sup>2</sup> ) <sup>2)</sup>	237.31	335.64	170.63	385.73	128.4	126.12	191.90
$t_{ip}$ (s) <sup>3)</sup>	27	60	15	114	24	15	57
(kW/m <sup>2</sup> ) <sup>4)</sup>	195.65	254.06	51.23	333.46	90.42	61.8	82.23
(kW/m <sup>2</sup> ) <sup>5)</sup>	142.45	158.56	26.48	219.35	83.22	38.93	65.20
THR (MJ/m <sup>2</sup> ) <sup>6)</sup>	41.4	38.4	6.4	53.0	54.6	10.2	22.7
$m_L$ (%) <sup>7)</sup>	98.9	100	100	98.8	84.5	60.6	89.0
(MJ/kg) <sup>8)</sup>	12.94	33.98	17.20	28.04	9.98	9.61	12.22
<i>Smoke</i>							
TSR (m <sup>2</sup> /m <sup>2</sup> ) <sup>9)</sup>	191.7	629.9	3.7	2135.6	5.3	13.0	1134.5
CO <sub>2</sub> yield (kg/kg) <sup>10)</sup>	1.39	2.39	2.30	2.15	1.28	2.98	1.29

Note 1) TTI: Time To Ignition; 2) pkHRR: Peak Heat Release Rate; 3)  $t_{ip}$ : Time to reach pkHRR; 4)  $\bar{Q}_{60}$ : Heat released at 60 s; 5)  $\bar{Q}_{180}$ : Heat released at 180 s; 6) THR: Total Heat Released; 7)  $m_L$ : mass loss rate; 8)  $\Delta H_c$ : Effective heat of combustion; 9) TSR: Total Smoke Released; 10) CO<sub>2</sub> yield: CO<sub>2</sub> production

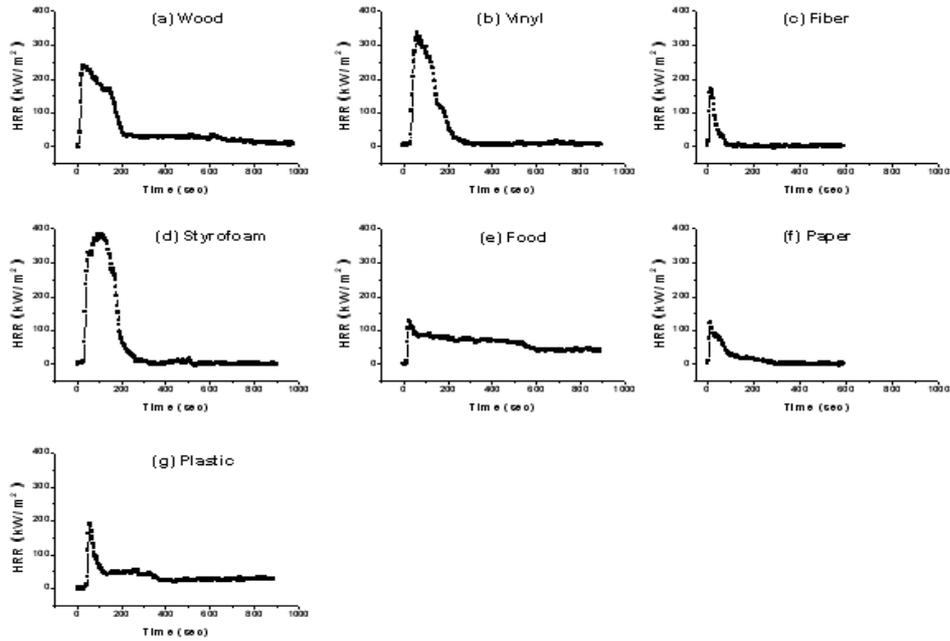


Fig 2. Heat release rates of the tested railroad waste.

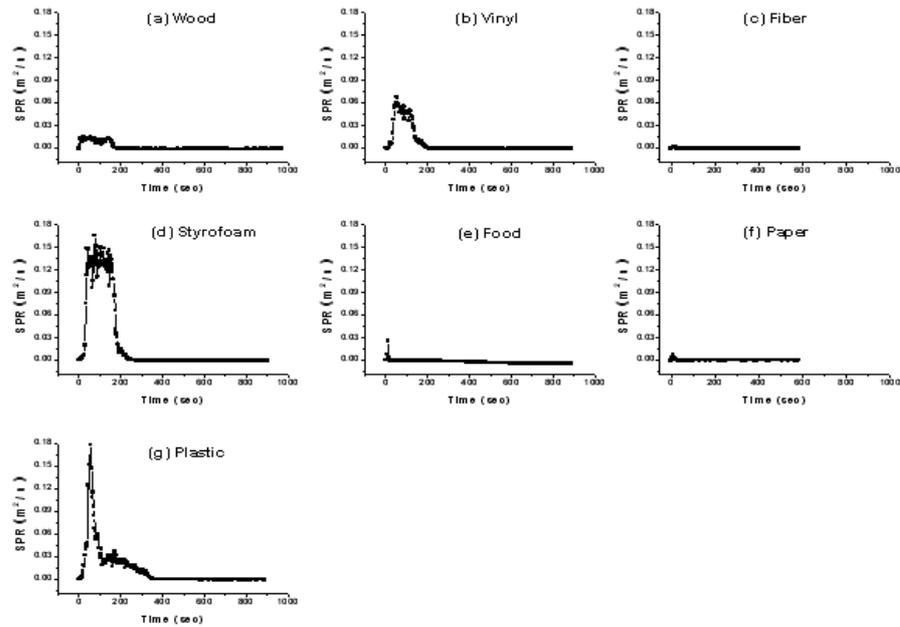


Fig 3. Smoke production rates of the tested railroad waste.

Figure 3 shows the smoke generated during sample incineration. The amount of smoke released by each item was in the order Styrofoam > plastic > vinyl > wood > food > paper > fiber. The amount of smoke released during biomass combustion was calculated using Bougure’s law, as shown in Equation (8). Smoke discharge was calculated using the extinction constant and flux (ISO TR 5660-2).

$$I = I_0 \exp(-\tau) \tag{8}$$

Here,  $I_0$  = intensity of incident radiation,  $I$  = intensity of transmitting radiation, and  $\tau$  = transmission distance.

As shown in Table 3, the total smoke released ranged from 3.7–2135.6  $m^2/m^2$ . Styrofoam had the highest smoke

release, at 2135.6  $m^2/m^2$ , while fiber exhibited the lowest at 3.7  $m^2/m^2$ . Compared to other waste types, the fiber released almost no smoke and had a shorter time between flare and the complete combustion. Smoke release from Styrofoam was ~500-fold more than that from fiber. As shown in Figure 3, of the three samples that released the most smoke, the smoke was extinct within 200 s after the flame flared in the case of Styrofoam and vinyl, while the smoke was released from plastic for a twofold longer duration (400 s). This indicates that Styrofoam, vinyl, and plastic railroad waste release a large quantity of smoke. In contrast, wood, fiber, food, and paper release very little smoke.

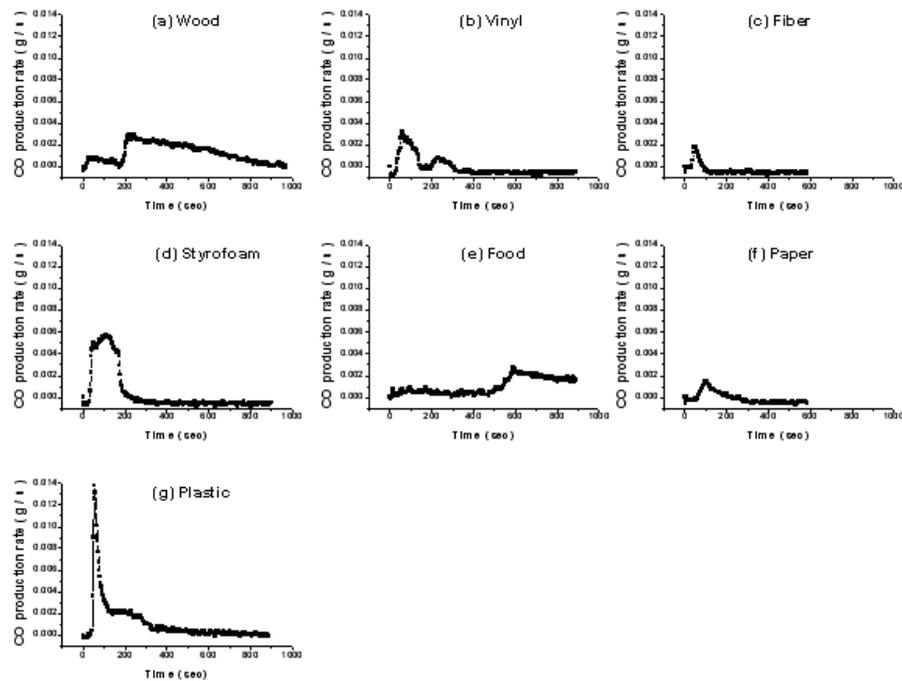


Fig 4. Carbon monoxide concentrations of the tested railroad waste.

Figure 4 shows the CO produced during incineration of railroad waste. The quantity of CO produced per item was in the order plastic > Styrofoam > wood > food > paper > fiber. Table 3 shows that plastic produced the highest amount of CO, at 0.014 g/s. Plastic, which recorded the highest CO production, produced instantaneously a large quantity of CO gas upon initiation of combustion. The amount then decreased gradually for 400 s. In comparison, Styrofoam continuously showed a wide peak from the

combustion start point, TTI, to 200 s. Vinyl showed a similar pattern to that of Styrofoam, albeit at a lower level. Wood and food showed different patterns. In the case of wood, some CO was produced at the beginning of combustion, which increased rapidly until the flame was extinguished at 200 s. Thereafter, some CO gas continued to be generated until the end of combustion. The food waste showed a similar pattern to that of the wood, interestingly, beginning at the 600-s timepoint.

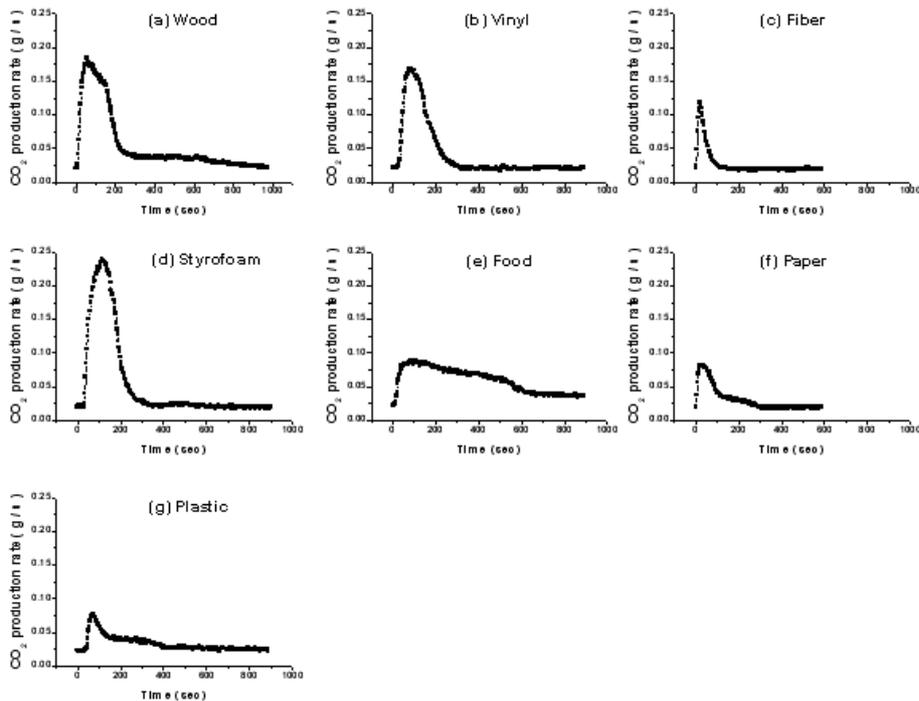


Fig 5. Carbon dioxide concentrations of the tested railroad waste.

Figure 5 shows CO<sub>2</sub> production during incineration of railroad waste. CO<sub>2</sub> production ranged from 1.28–2.39 kg/kg. CO<sub>2</sub> production was in the order Styrofoam > wood > vinyl > fiber > food > paper > plastic. All samples showed

the highest CO<sub>2</sub> production after the 100-s point. Notably, CO<sub>2</sub> production by food, unlike the other sample types, increased rapidly after TTI, which continued until test completion.

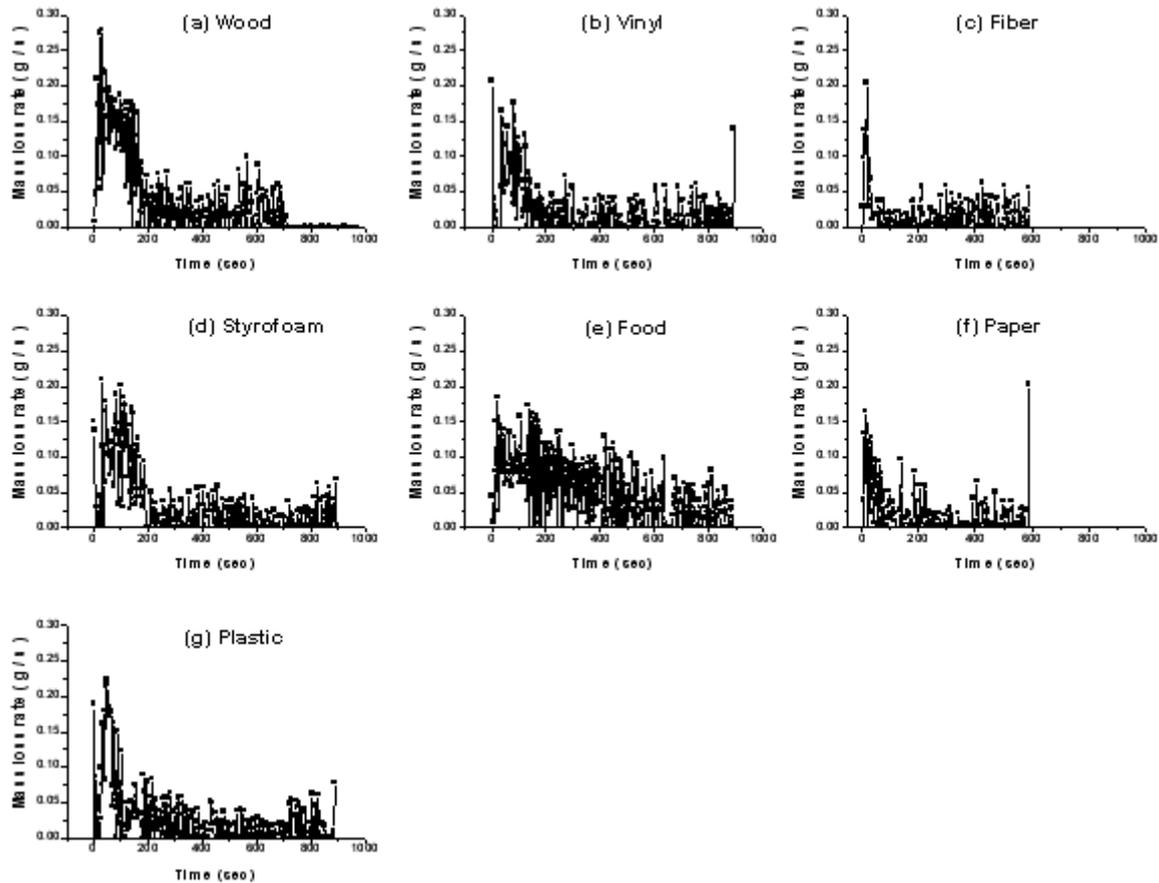


Fig 6. Mass loss rates of the tested railroad waste.

Figure 6 shows the mass loss rate ( $m_L \Delta E_b$ , %) of each railroad waste type. A high mass loss rate indicates dissipation of a greater amount of combustible content in a shorter time. Figure 6 and Table 3 indicate that the mass loss rates ranged from 60.6–100 %. The mass loss rate of vinyl and fiber were highest, at 100%. The mass loss rates of Styrofoam and wood were 98.8% and 98.9%, respectively, whereas those of food and plastic were 84.5% and 89.0%, respectively. Paper showed the lowest mass loss rate, of 60.6%. Incineration of samples at 50 kW for 1,200 s indicated that vinyl and fiber contained the highest contents of combustible materials, while paper had the highest ash content and the longest combustion time. Notably, the structure of the railroad waste sample was correlated with the mass change. Vinyl and fiber had the highest mass loss rates, likely due to their material structures. Waste other than paper, particularly vinyl and fiber, had many gaps between the particles even after being ground. In contrast, paper was ground into a fine powder and was densely structured with almost no gaps between the particles. The effective heat of combustion (MJ/kg) of the vinyl was 33.98 MJ/kg, while that of paper was 9.61 MJ/kg,

indicating that effective heat of combustion increased with greater mass loss rate.

## 4. Conclusion

For this study, we categorized waste from railroad operation into seven types; i.e., wood, vinyl, fiber, Styrofoam, food, paper and plastic. We then performed a combustion test using a cone calorimeter that is used widely for evaluating the combustion properties of combustible materials, to evaluate the heat release rate, smoke production rate, carbon monoxide production, carbon dioxide production and mass loss rate during biomass combustion. This section describes the conclusions of the study.

The time to the peak heat release rate of the railroad waste ranged from 3–42 s. The peak heat release rate of Styrofoam was highest, at 385.73 kW/m<sup>2</sup>. This is probably because Styrofoam has a greater carbon content, which is the heat source, than other samples, as shown by the elemental analysis. The total heat released from the samples ranged from 3.7–2135.6 m<sup>2</sup>/m<sup>2</sup>. Styrofoam was the highest-

performing waste material at 2135.6 m<sup>2</sup>/m<sup>2</sup>, and fiber was the lowest at 3.7 m<sup>2</sup>/m<sup>2</sup>. Compared to other railroad waste types, fiber released almost no smoke, and the time from ignition to complete combustion was shorter. Therefore, Styrofoam, vinyl and plastic railroad waste release a considerable quantity of smoke. In contrast, wood, fiber, food and paper release very little smoke.

Plastic, which showed instantaneous production of CO gas from the beginning of combustion, was highest CO producer, at 0.014 g/s. Furthermore, Styrofoam continuously showed a wide peak from the combustion start point, TTI, to 200 s. Vinyl showed a similar pattern to that of Styrofoam, albeit at a lower level. CO<sub>2</sub> production ranged from 1.28–2.39 kg/kg. The CO<sub>2</sub> production rate was in the order Styrofoam > wood > vinyl > fiber > food > paper > plastic. Notably food, unlike other samples, showed sudden gas generation after TTI, and continued producing CO<sub>2</sub> until test completion. The mass loss rate ranged from 60.6–100%; vinyl and fiber were highest, at 100%. Vinyl and fiber contained the highest contents of combustible materials, while paper had the highest ash content and longest combustion time. The higher mass loss rates of vinyl and fiber can be explained by their material structures. The effective heat of combustion ( $\Delta H_c$ ) of vinyl was 33.98 MJ/kg while that of paper was 9.61 MJ/kg, indicating that effective heat of combustion was higher as the mass loss rate increased.

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