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To cite this article: A. Nyombi, M R Williams & R. Wessling (2019): Toxic emissions from smouldering combustion of woody biomass and derived char with a case study of CO build-up in an ISO container, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, DOI: [10.1080/15567036.2019.1623348](https://doi.org/10.1080/15567036.2019.1623348)

To link to this article: <https://doi.org/10.1080/15567036.2019.1623348>



Published online: 30 May 2019.



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# Toxic emissions from smouldering combustion of woody biomass and derived char with a case study of CO build-up in an ISO container

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## ABSTRACT

Carbon monoxide (CO) from the use of biomass products causes some deaths in the United Kingdom every year. This study was undertaken to evaluate the amount of CO from five species of wood sawdust, and charcoal with a case study of CO in a confined ISO container. Laboratory experiments were conducted at temperatures between 350°C and 600°C under flowing air. Results showed a strong dependence of CO emissions on temperature and airflow. The CO emissions in the ISO container were above the recommended exposure limits due to poor ventilation.

## ARTICLE HISTORY

Received 20 January 2019  
Revised 28 March 2019  
Accepted 21 April 2019

## KEYWORDS

Carbon monoxide; sawdust; charcoal; temperature; airflow; confined space

## Introduction

Carbon monoxide (CO) produced by the combustion of carbonaceous solid fuels in the air can accumulate in confined spaces and interfere with the human oxygen-carrying capacity of blood (Blumenthal 2001). It is a potent yet odorless asphyxiant, with levels as low as 5000 ppm causing death in less than 30 min. In Denmark, between 2008 and 2012, there was approximately one accidental death per year from the burning of charcoal indoors (Nielsen, Gheorghe, and Lynnerup 2014). In the UK, CO/gas safety records indicate that 3% of the 719 deaths due to unintentional CO poisoning between 1995 and 2016 were caused by barbeques (Gas Safety Trust – UK 2017). In 2012, a young girl died in a tent in The New Forest (Whelan 2012), and Nicholas Holmes also died in a camper van in the same area and year (BBC-Online-News 2012). Hannah Thomas Jones died in Shropshire in 2013 from the same causes (BBC-Online-News 2013). There have been several other reports of unintentional/suicide carbon monoxide poisoning in confined spaces from biomass usage (Yoshioka et al. 2014; Madani et al. 1992; Huh et al. 2009; Chen et al. 2013; Fisher et al. 2013; Betten et al. 2013). One of the authors of this article was the survivor of a similar accident, in which his partner died (Stewart and Health 2015). In this incident, the couple were convinced that the fire was out when they took the barbeque into their tent. This tragic accident was the event that prompted the studies described in this article.

Ideally, the combustion products of carbonaceous fuels would be entirely converted to CO<sub>2</sub>, moisture and other harmless products at all temperatures because these are far less toxic than CO, and the combustion reaction would be thermodynamically more efficient. The relative amounts of CO released by solid fuels during combustion can be influenced by the combustion temperature and by the amount of oxygen in the air. Solid fuels like sawdust and charcoal burn at their surfaces, where fuel-rich conditions predominate and the amount of air (oxygen) is likely to be insufficient for complete

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combustion (Flagan and Seinfeld 1988). The fuels generally reach temperatures of 700–800°C during natural combustion. However, more literature and information is needed about the effects of mid-level temperatures (300–600°C) on the emission of CO from burning sawdust and charcoal.

Compressed sawdust briquettes have found wide applications in domestic and industrial applications as alternatives/supplements to wood logs, charcoal and fossil fuels (Sánchez, Pasache, and García 2014; Chembukulam et al. 1981). Derived from wood waste materials, wood sawdust briquettes are easy to make with simple technologies and low production costs (Hosseinizand, Sokhansanj, and Jim Lim 2018; Zamorano et al. 2011). Wood waste in the UK constituted 1.645 million tonnes in 2018 while packaging materials (paper & cardboard) constituted 4.749 million tonnes. Wood constituted 1.31 million tonnes in 2016 (Department for Environmental Food & Rural Affairs – DEFRA – Government Statistical services) (UK – DEFRA 2018). An estimated 10 million tonnes of ‘post-farm gate’ food waste is thrown out across the UK every year, of which only 1.8 million tonnes was recycled as per 2016 (UK – DEFRA 2018). Forestry waste and agricultural wastes (Lazaroiu et al. 2017) are also good raw materials for making compressed sawdust logs/briquettes. Conversion of such carbonaceous materials to useful energy is a viable solution, to fill the energy gap left by the declining fossils as well as reducing the wastes sent to landfills and minimizing deforestation.

The use of raw biomass materials for heating in fireplaces has been ongoing for many years since the invention of fire. The use of wood boilers from the 1970s and subsequent developments until today saw a remarkable stride in the utilization of biomass materials in homes (Tarm Biomass 2018; Josua and Wood Pellet Boiler Solutions 2012). However, the combustion of such carbonaceous materials emits several pollutants of which CO and CO<sub>2</sub> constitute over 80% of the total emissions (Lupa et al. 2013).

Quantifying the emissions from raw biomass combustion is vital to assess the burden against which sustainable solutions can be sought to minimize the danger of human intoxication especially from CO. Much as acute exposure to CO emissions from raw carbonaceous waste has been reported (Naeher et al. 2007; Muala et al. 2015), there is continuous exposure to chronic levels of pollutants (Green et al. 1999). Several studies have analyzed CO emissions from wood materials: Bhattacharya et al. (2002) compiled the data for emissions of CO from the wood used in developing countries, and the emission values were in the range 50–300 g/kg. However, some portable wood burning stoves (Fan and Zhang 2001) were reported to be efficient at minimizing CO emissions to as low as 0.3–1.6 mg/g.

Much as wood and wood sawdust are used extensively, the derived product – charcoal, has found even more wide application due to high energy content, less smoke, easy of ignition and transport among other advantages. However, since the elemental carbon is more concentrated in charcoal than wood logs or wood sawdust, the amounts of CO emitted from incomplete combustion of charcoal are considerably higher. In one investigation of CO emissions from indoor barbecue charcoal, the authors tested temperatures in the range 450–550°C with linear air flow rates of 10 and 20 L/s in a tube furnace (Huang, Lee, and Wu 2016). In their study, the temperature had no significant influence on CO emissions during the combustion of charcoal, but the effect of air flow was not discussed. A comparison of emissions from flaming and smoldering biomass and other solid fuels revealed that smoldering fuel produces more CO than flaming fuel (Mitchell et al. 2016). An analysis of the emissions from coal braziers revealed that high ventilation rates reduce the levels of CO and other emissions from burning coal (Tafadzwa et al. 2017).

Several studies have been carried out to investigate CO emissions from charcoal under normal combustion conditions. Ojima (Ojima 2011) investigated the rate of CO generation from burning charcoal to determine the ventilation required in a room to maintain the CO levels below the Japanese national threshold. Evans and Emmons (Evans and Emmons 1977) produced an equation for burning charcoal which linked the CO/CO<sub>2</sub> ratio to temperature.

The desire to minimize heat loss in confined spaces has resulted in embracing double-glazed window or door houses as a new fashion. This has its own drawbacks; combustion pollutants easily

built-up leading to chronic and sometimes acute exposures. For the case of CO, since it is colorless and odorless, the victims are taken unaware with the feeling of tiredness, headache, and similar conditions which are related to other ailments. It is natural that when a person gets such feelings, they resort to resting/sleeping. In such a CO environment, the consequences may be fatal or sustaining serious injuries.

Confined spaces usually have incomplete mixing of air (Barber and Ogilvie 1982; American-Conference-of-Governmental-Industrial-Hygienists 1998) and hence pollutants from combustion form different layers with concentrations increasing with height depending on ambient temperature and air buoyancy within the confined space. The longer a solid fuel is burnt in a confined space, the higher the likelihood that CO levels will go beyond the set threshold limit values (Francisco, Gordon, and Rose 2010). Burning barbecue (BBQ) charcoal with ignition enhancers usually produces smoke during the first stages which many users avoid due to unpleasantness, but it usually clears away soon. However, the maximum concentrations of CO are produced during the smoldering phase when there is no smoke (Crewe et al. 2014).

Different organizations have set maximum exposure limits for CO; the WHO (2011, 2010) has established 100 mg/m<sup>3</sup> (90 ppm) for 15 min, 60 mg/m<sup>3</sup> (50 ppm) for 30 min, 30 mg/m<sup>3</sup> (25 ppm) for 1 h, 10 mg/m<sup>3</sup> (10 ppm) for 8 h. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm parts of air (55 mg/m<sup>3</sup>) as an 8-h time-weighted average (TWA) concentration. The National Institute for Occupational Safety and Health (NIOSH) has established a recommended exposure limit (REL) for CO of 35 ppm (40 mg/m<sup>3</sup>) as an 8-h TWA and 200 ppm (229 mg/m<sup>3</sup>) as a ceiling. The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned CO a threshold limit value (TLV) of 25 ppm (29 mg/m<sup>3</sup>) as a TWA for a normal 8-h workday and a 40-h workweek (American Conference of Governmental Industrial Hygienists (ACGIH) 2013; DHHS-NIOSH 2004).

The main goal of most recent studies has been to facilitate the design of more efficient cooking stoves (Bhattacharya and Abdul Salam 2002; Jetter et al. 2012; Tanetsakunvatana and Kuprianov 2007) and ventilation systems (Ojima 2011), the development of standards for stoves (Jetter et al. 2012) and biomass space-heating equipment (Koyuncu and Pinar 2007), the comparison of solid fuel emissions (Smith et al. 1993), the design and building of air samplers, and the development of low-emission combustion technologies. In this study, we investigated the effect of temperature and air flow on CO emissions during the mid-temperature smoldering combustion of wood sawdust and wood charcoal in a tube furnace system under flowing air. We also give a detailed case study of CO accumulation in confined space. This work clearly highlights and tries to quantify the hazard due to the evolution of carbon monoxide from “low” temperature pyrolysis of sawdust and charcoal especially during the cooling phase following cooking or heating with such fuels. Most other studies have looked at normal combustion at around 800°C whereas the significant evolution of carbon monoxide occurs at 400°C. Ignorance of this hazard has led to deaths in recreational situations such as camping and boating.

## Methodology

### Sawdust

The samples were obtained from five different wood species; ash (*Fraxinus Excelsior*), beech (*Fagus Sylvatica*), elder (*Sambucus Nigra*), lilac (*Syringa Vulgaris*), and Hazel (*Corylus Avellana*). These were crushed using a laboratory vibratory pulveriser and sieved through a 210 µm mesh. The samples were dried in an oven at 110°C overnight and kept in sealed containers for subsequent analysis. The proximate and ultimate analysis for these samples are shown in Table 1. The calorific values were determined using a method described elsewhere (Toscano and Pedretti 2009). For determination of carbon monoxide (CO) emissions, triplicates of 0.2 g samples were pyrolyzed under air at temperatures between 300°C and 450°C using a method described in our previous work (Nyombi, Williams, and Wessling 2019b). The duration of the experiments varied between 5 and 7 min. The experiments

**Table 1.** Ultimate (wt%), proximate analysis (wt%) and heating values (MJ/kg) of the samples.

Sample name	Ultimate analysis $\pm 0.1$				Proximate analysis $\pm 0.1$				<sup>e</sup> HHV $\pm 0.2$	Source
	N	C	H	O*	M <sup>a</sup>	VM <sup>b</sup>	FC <sup>c</sup>	RA <sup>d</sup>		
Lilac wood	0.30	49.19	6.63	43.87	5.8	73.2	19.5	1.5	19.15	This study
Ash wood	0.35	49.12	6.64	43.89	5.3	71.0	20.6	3.1	19.12	This study
Ash tree	<0.1	48.9	5.9	44.9	7.6	86.8	12.3	0.9	17.23	(Nyombi, Williams, & Wessling, 2018)
Hazel wood	0.51	48.41	6.60	44.48	4.9	75.7	18.2	1.2	18.75	This study
Elder wood	0.27	48.88	6.49	44.36	6.3	71.7	19.3	2.5	18.86	This study
Beech wood	0.35	49.07	6.67	43.92	5.8	75.8	17.7	0.8	19.12	This study
Lilac char	0.62	83.44	2.74	13.21	3.5	11.7	80.9	4.0	32.18	This study
Ash char	0.49	80.67	2.80	16.04	4.1	13.8	78.2	3.9	30.87	This study
Hazel char	1.08	83.11	2.81	13.00	3.8	12.0	80.5	3.7	32.13	This study
Hazel nut shell	-	75.00	5.50	40.60	-	20.6	77.1	2.3	-	(Demirbas & Demirba, 1999)
Elder char	0.49	83.79	2.93	12.79	3.9	11.5	80.6	4.1	32.52	This study
Beech char	0.74	80.58	2.74	15.95	5.2	14.5	75.9	4.3	30.79	This study
Beech wood char	0.30	89.00	1.70	9.00	-	-	-	-	-	(Klose & Wölki, 2005)
Beech char	-	80.00	2.00	18.00	-	-	-	-	-	(Antal & Grønli, 2003)
Coal char	1.16	82.74	3.56	12.54	2.0	11.3	80.1	6.5	32.68	This study
Bituminous coal	1.60	81.30	5.30	10.80	14.6	35.2	46.2	4.0	-	(Scala, 2009)
Commercial char	0.25	84.02	2.15	13.58	4.3	9.5	60.4	25.9	31.86	This study
Bagasse char	0.47	79.40	3.60	16.60	-	27.0	64.0	10.5	-	(Katyal, 2007)

\*Determined by difference, <sup>a</sup>Moisture content, <sup>b</sup>Volatile matter, <sup>c</sup>Fixed carbon, <sup>d</sup>Residual ash, <sup>e</sup>Higher heating value

were terminated when the data logger registered zero concentration for CO meaning that the concentrations were below the detection limit of the sensor. The triplicates for each parameter were averaged to give a single data set.

## Charcoal

The char samples were prepared in the laboratory in a furnace at 500°C isothermal temperature for 4 h. Upon cooling, the charcoal samples were ground to a fine powder using an Essa LM2 pulverising mill and were sieved through a 210 µm mesh before drying in an oven at 105°C and storing in a sealed container. The moisture content, volatile matter, fixed carbon and residual ash were determined as per the method described in our previous work (Nyombi, Williams, and Wessling 2018).

For determination of carbon monoxide (CO) emissions, triplicates of 0.2 g samples were heated under air at temperatures between 350°C and 600°C using a method described in our previous work (Nyombi, Williams, and Wessling 2019b).

## CO emission computation

The overall amounts of the CO were determined by first calculating the area under the concentration-time curve using Equation (1), and then presenting the data in ppm.s

$$A_T = \sum_{t_0}^{t_f} t_n C_n \quad (1)$$

where  $A_T$ ,  $t_0$ ,  $t_f$ ,  $t_n$  and  $C_n$  are the total area under the CO curves, initial time, final time,  $n^{\text{th}}$  time, and concentration at the  $n^{\text{th}}$  time, respectively.

The total area was then used to calculate the total moles of CO evolved using Equation (2), which involves the air flow rate and molar volume over the time of the experiment.

$$X_i = \frac{A_T Q}{60 V_{\text{rtp}} 10^6} \quad (2)$$

where  $X_i$ ,  $Q$  and  $V_{\text{rtp}}$  are the moles of CO, air flow rate, and molar volume at room temperature and pressure, respectively.

The CO emissions (mg/g) were calculated by determining the mass of CO (Moles x relative molecular mass x 1000) and dividing it by the dry basis mass (in grams) of the original sample.

### ***A case study of CO in the ISO container***

The experiments were carried out in a 33m<sup>3</sup> ISO container with a double door (dimensions = L x H = 2.34 m x 2.28 m) and no windows. However, the container was not air tight even in the fully closed position. One kilogram (1 kg) of BBQ charcoal in a paper bag was loaded on to a barbecue pan that was fixed on a 25 kg type load cell which had been calibrated prior to the experiments. Three K type thermocouples were inserted into the charcoal before it was ignited. The thermocouples and load cell were connected to a Squirrel data logger that recorded the temperature and mass loss of the charcoal during the experiments. Two fans (10 cm diameter) were fixed one on each side of the BBQ pan blowing air at a velocity of 3.5m/s towards the charcoal to allow quick distribution of combustion gases in the ISO container.

The CO emissions were recorded by auto-logging PHD6 instruments fitted with CO electro-chemical sensors. The CO recording instruments were placed inside the container at 30 cm above the floor and near the door at 150 cm above the floor. These PHD6 instruments also recorded room temperature. For the safety of the research team, another set of CO sensor was placed outside the container fitted with a suction pump to draw effluent gases from near the BBQ inside the container. This was connected to the data logger that was checked routinely to monitor the concentrations of CO. Once the CO concentrations went below 10 ppm, the experiment was terminated. Four domestic CO alarms (Kidde type, model 10LLDCO) were installed near the ceiling of the container. These were used to record the time when the alarm went off from the start of each experiment as they responded to time-weighted-average exposures, and the maximum concentrations recorded during each run. Each set of experiments was repeated three times.

A portable weather station was installed just outside the container for monitoring wind speed, humidity, temperature, and dew point. The wind speeds were in the range 3.53 to 6.5 (m/s), the outside temperatures were in the range 17.3 to 19.6 (°C), pressure of approximately 1020.7 mbar, and the dew point was in the range 12.2 to 15.2 (°C). The mass of charcoal used per experiment was in the range 900–930 g. Each experiment lasted about 2 h.

## **Results and discussion**

### ***Wood sawdust***

#### ***Effect of temperature***

The experiments were conducted for the temperature range 300–450°C for two main reasons: (i) below 300°C, the emissions of CO were too low to be detected; (ii) above 450°C, the combustion process transformed from smouldering to flaming (Li, Paul, and Czajka 2016). Hence, any experiment in which no gaseous concentrations were detected within the first 5 min was terminated and disregarded. Likewise, for any experiment where the combustion system transformed from smoldering to flaming was also terminated and disregarded.

The tendency of combustion to transform from smoldering to flaming could be related to the concentration of volatiles within the sawdust samples. However, some studies suggest that some mineral elements, especially potassium, enhance the temperature of samples leading to enhanced combustibility (Jones et al. 2015).

The concentration of CO (mg/g) at each temperature can be seen in Table 2. The essential gases produced during smoldering are CO and CO<sub>2</sub> accounting for over 80% (Lupa et al. 2012) of the total gaseous emissions. Except for beech and ash (*Fraxinus*) (at 300°C only), all samples registered CO values in the range 150 ≤ CO ≤ 250 (±~11) mg/g for all temperatures. These results are consistent with the 50–300 mg/g detected by Burnet et al. (1986) from wood fire stoves, but higher than the 0.3–1.6 mg/g detected by Cheng-Wei (Fan and Zhang 2001) emitted by portable



household warming devices. The influence of temperature on emissions of CO from this study cannot be generalized. Beech and hazel samples showed a general increase; lilac CO emissions remained almost constant, Ash (*Fraxinus*) CO emissions increased at 300–350°C followed by a decrease to 450°C. Elder showed a general decrease in CO emissions with temperature attributed to enhanced combustion efficiency (Duan et al. 2013). Xiao et al. (2015) determined the emissions of CO from a moving grate boiler to be in the range 49–56 mg/g. The amounts of CO emissions recorded in our study are high, and without sufficient ventilation, these values could lead to acute exposure symptoms in a healthy individual especially in a confined space.

### ***Effect of airflow***

There was a general decrease in CO emissions with airflow Table 2. This could be due to the increased turbulence created by the supply of increased air, which resulted in better combustion of volatile matter (Srinivasa Rao and Reddy 2008 ; Duan et al. 2014). This may also be due to the complete combustion of smaller particles and unburned carbon (Duan et al. 2013). None the less the obtained values exceed the WHO limits. Casey et al. (2018) determined the CO time-weighted averages in several homes in Navajo of Japan and found the values (>40 ppm per 8 h weighted average) to exceed the recommended levels.

### ***CO evolution profile from wood sawdust***

Average data values were produced for each triplicate analysis. All CO evolution pattern followed a comparable trend similar to that reported elsewhere (Lupa et al. 2013) and reached the minimum values at periods between 300 and 500s for all samples. For this reason, lilac (*Syringa vulgaris*) was chosen to represent all the other sawdust samples Figure 1 for the evolution profiles. The key observations were: (i) The time required to attain the maximum CO concentration, and the total time of the experiment decreased with increase in temperature across all airflows (Knudsen et al. 2012). This was attributed to the quick degradation of the cellulose, hemicellulose and lignin components with an increase in temperature. (ii) There was a general increase in the maximum concentration of CO with an increase in temperature across all airflows. This was related to the early-peak-phenomena in which the concentration of products is directly proportional to temperature (iii) For a particular temperature, the maximum CO concentrations decreased with an increase in airflow (Farokhi, Birouk, and Tabet 2017). This was attributed to CO oxidation by oxygen in the air.

We also observed the appearance of a secondary peak towards completion of the emission profiles especially at low airflow rates and low temperatures. The second peak was attributed to CO emissions from devolatilised char which is rich in carbon.

### ***Charcoal***

The proximate and ultimate analysis values of charcoal shown in Table 1, are consistent with other studies (Strezov et al. 2007; Cao et al. 2012). The low volatile matter content of commercial charcoal could be attributed to the temperature at which it was manufactured; high temperatures remove most of the volatiles (Huang, Lee, and Wu 2016).

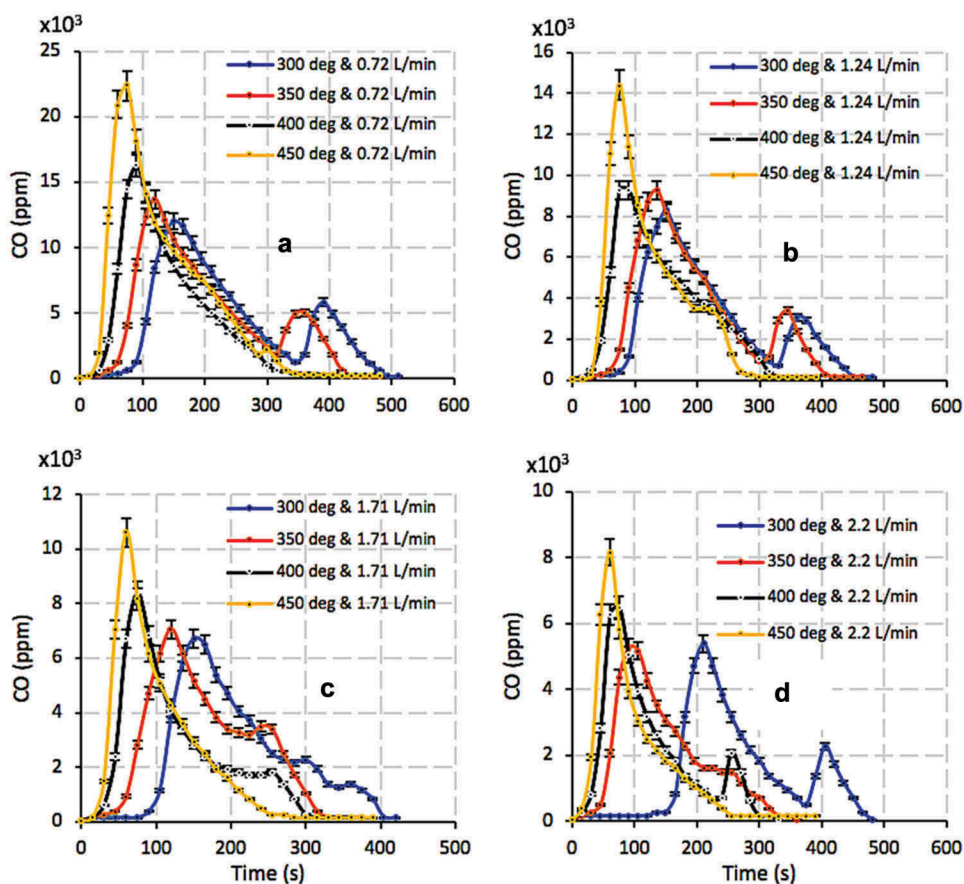
### ***Effect of temperature and air flow***

There was a general decrease in CO emissions with temperature across all airflows Table 3. The CO evolution profile followed a general pattern shown in Figure 2 for all charcoal samples. The initial CO evolution is a typical zero order followed by a first-order decay until most of the carbon is

**Table 2.** Effect of temperature and airflow on emissions of CO  $\pm$  STD (mg/g) from wood sawdust samples. The values were computed with one standard deviation.

Sample	Temperature (°C)				Airflow (L/min)			
	300	350	400	450	0.72	1.24	1.71	2.2
Lilac wood	122.7 $\pm$ 3.4	124.0 $\pm$ 7.8	117.5 $\pm$ 6.6	128.3 $\pm$ 5.6	129.5 $\pm$ 12.8	125.6 $\pm$ 4.5	123.4 $\pm$ 8.5	114.1 $\pm$ 4.0
Elder wood	172.3 $\pm$ 3.9	167.2 $\pm$ 6.8	162.4 $\pm$ 4.5	161.8 $\pm$ 14.1	165.6 $\pm$ 8.2	176.6 $\pm$ 7.8	167.2 $\pm$ 5.9	159.1 $\pm$ 7.8
Hazel wood	-	185.01 $\pm$ 3.8	245.5 $\pm$ 8.1	258.0 $\pm$ 8.6	233.7 $\pm$ 5.7	230.6 $\pm$ 4.5	242.6 $\pm$ 8.9	211.1 $\pm$ 6.9
Ash wood	136.6 $\pm$ 8.8	204.5 $\pm$ 8.4	189.7 $\pm$ 10.9	169.8 $\pm$ 10.5	201.2 $\pm$ 13.9	182.1 $\pm$ 7.9	155.6 $\pm$ 4.2	170.0 $\pm$ 10.7
Beech wood	98.9 $\pm$ 8.1	170.2 $\pm$ 6.8	173.6 $\pm$ 9.0	166.0 $\pm$ 5.9	179.3 $\pm$ 6.2	153.6 $\pm$ 4.0	131.7 $\pm$ 7.9	159.0 $\pm$ 6.1





**Figure 1.** CO emission profile for lilac (*Syringa vulgaris*) representing the profiles for all sawdust samples in this study. A – at 0.72 L/min; B – at 1.24 L/min; C – at 1.71 L/min and D – at 2.2 L/min airflow rates.

consumed. Apart from beech charcoal, the rest of the charcoal samples showed a general decrease in CO emissions with airflow Table 4.

The time-dependent decay of CO emissions is probably related to the turnover of surface complexes, their attachment (weak or strong) and subsequent loss (Nyombi, Williams, and Wessling 2019a). At any point on the decay curve, the rate of release (calculated from ppm data and flow rates as moles/s) can be related to the remaining mass of charcoal, and “rate constants” calculated. Although we did not measure the mass of charcoal continuously during the heating process, the number of moles remaining at any point can be estimated from the moles of CO and CO<sub>2</sub> released. The rate of CO production was linearly dependent on the amount of carbon remaining for most part of each experiment, Figure 3.

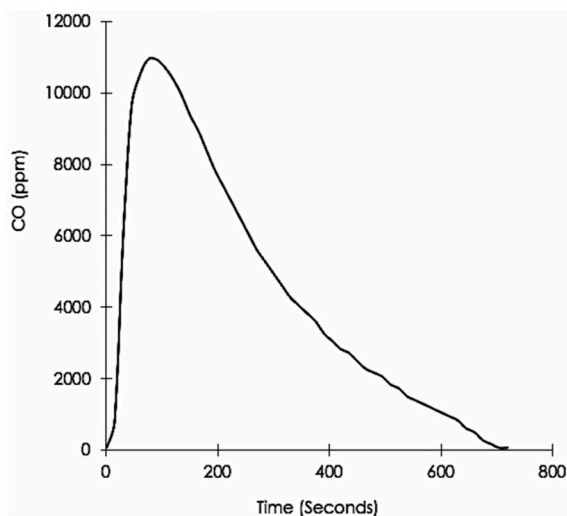
Rate constants ( $k_s$  in units of 1/s) can be derived if the linear data for CO in Figure 3 are used in Equation (3) which shows a simple pseudo-first-order reaction assuming [O<sub>2</sub>] is constant and the surface area of carbon decreases uniformly with mass. These data are shown in Table 5.

$$\frac{d[\text{CO}]}{dt} = k_s \cdot [\text{Carbon}] \quad (3)$$

We again observe an airflow effect, with low flows increasing the rate constant for CO evolution, and a temperature effect that is only manifested at the lower air flows.

**Table 3.** Effect of temperature on emissions of CO ± STD (mg/g) from charcoal samples. The values were computed with one standard deviation.

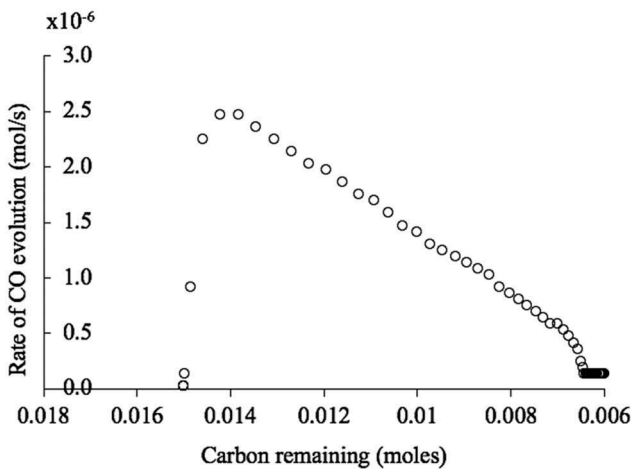
Sample	Temperature (°C)					
	350	400	450	500	550	600
Commercial charcoal	98.1 ± 9.6	198.0 ± 9.9	258.2 ± 10.2	265.3 ± 11.8	245.9 ± 15.2	236.6 ± 15.6
Lilac charcoal	303.9 ± 10.2	287.5 ± 3.2	275.4 ± 7.0	257.5 ± 13.9	251.3 ± 10.3	296.47 ± 5.5
Ash charcoal	299.0 ± 12.8	286.6 ± 13.6	300.6 ± 17.7	291.3 ± 11.7	273.0 ± 16.0	272.2 ± 10.2
Elder charcoal	301.9 ± 14.5	331.8 ± 7.0	324.4 ± 14.7	305.4 ± 19.9	272.2 ± 10.5	275.7 ± 13.2
Hazel charcoal	347.9 ± 11.5	397.6 ± 12.6	465.5 ± 11.8	495.0 ± 10.5	403.6 ± 9.8	363.7 ± 12.1
Beech charcoal	300.6 ± 12.1	328.6 ± 15.4	334.1 ± 15.6	327.9 ± 17.0	308.5 ± 17.9	276.0 ± 10.7



**Figure 2.** Typical profile for the release of CO from charcoal.

**Table 4.** Effect of airflow on emissions of CO  $\pm$  STD (mg/g) from charcoal samples. The values were computed with one standard deviation.

Sample	Airflow (L/min)			
	0.72	1.24	1.71	2.2
Commercial charcoal	257.8 $\pm$ 16.1	210.9 $\pm$ 12.9	186.6 $\pm$ 12.7	212.7 $\pm$ 17.4
Lilac charcoal	265.4 $\pm$ 13.4	292.6 $\pm$ 17.7	282.7 $\pm$ 12.9	273.9 $\pm$ 13.3
Ash charcoal	264.0 $\pm$ 16.1	306.7 $\pm$ 10.2	291.2 $\pm$ 14.1	286.6 $\pm$ 14.3
Elder charcoal	318.8 $\pm$ 17.3	297.7 $\pm$ 12.7	286.7 $\pm$ 18.2	304.3 $\pm$ 13.6
Hazel charcoal	426.8 $\pm$ 10.2	421.6 $\pm$ 14.5	408.7 $\pm$ 14.6	391.6 $\pm$ 18.2
Beech charcoal	299.2 $\pm$ 16.7	303.2 $\pm$ 14.5	315.0 $\pm$ 11.9	333.0 $\pm$ 18.6

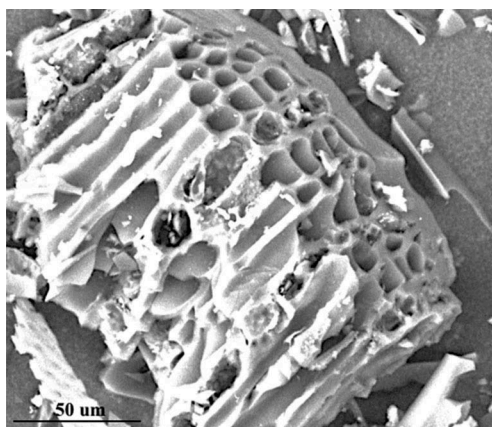


**Figure 3.** The rate of evolution of CO from char at 450°C and 1.71 L/min air flow.

Scanning electron microscopy, [Figure 4](#), revealed that the wood char retains much of the micrometer-sized porous structure of the wood from which it was derived. Wood charcoal probably burns in much the same way on all surfaces similar to propellant grains (Bailey and Murray [1989](#))

**Table 5.** Values of  $k_s$  (1/s) for different temperatures and air flow rates.

Temp (°C)	(Air flow $\pm$ 0.01) (L/min)			
	0.72	1.24	1.7	2.2
400	$5.3 \times 10^{-4}$	$3.9 \times 10^{-4}$	—	$2.2 \times 10^{-4}$
450	$5.3 \times 10^{-4}$	$3.4 \times 10^{-4}$	$2.7 \times 10^{-4}$	$2.2 \times 10^{-4}$
500	$4.5 \times 10^{-4}$	$3.4 \times 10^{-4}$	$2.7 \times 10^{-4}$	$2.4 \times 10^{-4}$
550	$7.7 \times 10^{-4}$	$4.5 \times 10^{-4}$	$2.8 \times 10^{-4}$	$2.5 \times 10^{-4}$
600	$8.8 \times 10^{-4}$	$6.8 \times 10^{-4}$	$3.6 \times 10^{-4}$	$2.3 \times 10^{-4}$

**Figure 4.** Scanning electron microscopy image for wood charcoal.

extruded with voids down their length so that as the external surface shrinks during burning, simultaneously the internal surface grows to maintain the overall surface area thus conferring a near constant burn rate. Hence, the assumption that surface area depends on the mass of charcoal could be true.

### ***$\Delta G$ as a predictor of reaction feasibility***

Several reactions may take place during char combustion leading to the production of CO, including the following:



We predict that reactions 4 become less favorable as the temperature increases, whereas 5 become more favorable because the former involve a decrease in gas-phase species and the latter an increase. Reaction 6 does not occur at temperatures below 973 K (Dollimore et al. 1970).

There are many other factors to consider. The product ratios (CO/CO<sub>2</sub>) may reflect the different active sites present on each char surface associated with cationic trace metal impurities that act as catalysts (Tognotti, Longwell, and Sarofim 1990). Although our experiments involved isothermal combustion, the actual char temperatures could have been higher because metal impurities can enhance the burning temperature of char (Pohl 1986). There is evidence for CO conversion to CO<sub>2</sub> at the char surface by the catalytic action of the char mineral matter (Mccollor et al. 1988). It is also

possible that the decrease in CO amounts with temperature are due to secondary processes taking place in the charcoal pores, promoting the conversion of CO to CO<sub>2</sub>.

Our results highlight the dangerous assumption that charcoal fires do not produce CO merely because they are not glowing red hot. Radiant heat should be an indicator of continuing combustion. Initial results with this charcoal sample suggest that there are steps that could be taken to encourage secondary conversion of CO to CO<sub>2</sub> in these systems and that this may be as simple as selecting the most suitable wood for charcoal preparation, the appropriate conditions and proper usage.

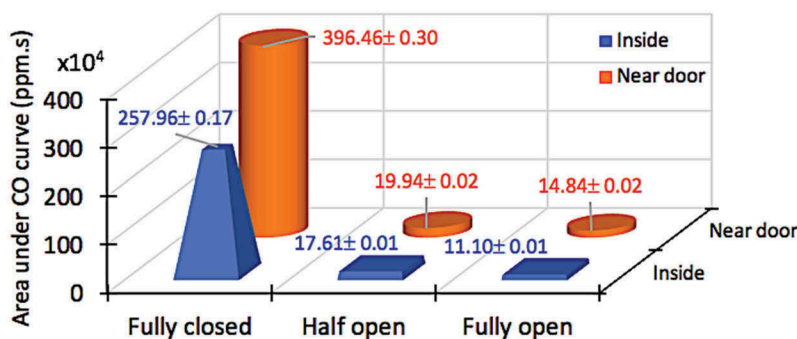
### Case study of CO in the ISO container

#### CO at different positions in the container

The results clearly show that the CO values recorded at 150 cm above floor (near the door) were higher than those recorded at 30 cm above floor (extreme end inside the container), [Figure 5](#). This could be explained by the movement of heavy, moist and fresh air from the outside displacing dry, warm and polluted air from charcoal combustion to the upper parts of the container ([De Nevers 2004](#)). Secondly, the buoyant air movement and the temperature difference within the ISO container was a major factor contributing for movement of CO to the upper parts of the ISO container ([Zhigang 2006](#)). This emphasizes two very important considerations during cooking/heating: to keep the door and windows open to allow entry of fresh air ([Hughes and Mak 2011](#)) and to move at the lower side as possible (in a crawling position) as we exit any confined space on fire. As expected, the amounts of emissions relative to the door position were in the order; fully closed > half open > fully open. Even in the fully closed-door position, fresh air could enter since the door was not air tight ([Hekal and El-Maghlany 2017](#)).

There was a steady decline in charcoal temperature recorded during the fully closed-door session reaching its lowest value (159°C) at the end of the experiment compared to the fully open and half open-door positions which had the lowest charcoal temperature as 442°C and 500°C, respectively ([Li, Paul, and Czajka 2016](#)). This could be attributed to low air flow within the container during the fully closed-door position, hence, residual ash built-up on charcoal surfaces and could not be easily removed due to low airflow rates. This also explains the high amounts of CO recorded during this experiment due to low purging compared to the fully open and the half open door positions. Additionally, due to the constant blowing of air, the temperature during the fully open and half open experiments was maintained above 440°C ([Spence, Buchmann, and Jermy 2007](#)) throughout the experiment compared to the fully closed-door position where the charcoal temperature declined continuously to as low as 159°C.

The fully open-door experiment took about 110 min, the half open experiment took about 120 min while the fully closed-door experiment took the longest time of close to 140 min. This could be



**Figure 5.** Area under the CO curves for the different door positions during the ISO container experiments.

due to the oxidation of charcoal by incoming air: the higher the airflow, the faster the oxidation (Nijhuis et al. 1997).

Even when charcoal looks to be out of fire, it is not recommended to take it to any confined space. The best practice would be to empty the charcoal remaining into a waste/hot charcoal safety bin before storage of the BBQ grill. In the 33 m<sup>3</sup> ISO container experiment described above, CO values as high as 70 ppm were recorded from only 270 g of (charcoal+ residual ash) which had remained after the 1 kg charcoal sample was burnt from the outside – this was done to simulate what some CO poisoning victims do after a BBQ meal. This implies that any confined space smaller than the ISO container used in this study could have registered very high CO concentrations (Svedberg et al. 2004).

The domestic alarms also provided very important information. In the fully open position, the alarms went off at 22 to 25 min within the experiment. Once checked at the end of the experiments, they recorded maximum CO concentrations as 125 to 130 ppm. In the half open door position, the alarms went off at 15 to 20 min within the experiment and they recorded 820 to 900 ppm as maximum CO concentrations. In the fully closed-door position, the alarms went off at 2 to 6 min and they recorded 999 ppm as maximum CO concentrations during those experiments. With the charcoal burnt from the outside and then taken inside the ISO container, the CO alarms went off after 40 min. According to the manufacturers of Kidde alarms (Kidde-United-Technologies 2018), the alarm response times and CO concentration are shown in Table 6.

The experimental alarm response values (CO concentration and time) agree with the guide from the manufacturers of Kidde alarms. In the fully open-door position, the alarm response time was within the 15-min allowable limits but outside the 1-h limits of UK/EU/WHO (WHO 2010) guideline. In the half open and fully closed-door positions, the recorded values all exceed the UK/EU/WHO guideline values for 15 min (100mg/m<sup>3</sup> or 87.3 ppm) and 1 h (35mg/m<sup>3</sup> or 30.6 ppm) indoor exposures.

### **Experimental CO levels in relation to recommended exposure limits**

In the fully closed-door position, the overall time-weighted-average (TWA) CO concentration for the entire experiment (2 h and 20 min) at 150 cm was 497 ppm. This level is said to cause mild headache, fatigue, nausea and dizziness (Euan and Nicholas 2016; WHO 2011). However, the 1-h time-weighted average CO value was 751 ppm. This value is close to 800 ppm established by OSHA that causes serious headache and may trigger other symptoms that are life-threatening. In the sitting position (at 30 cm), the 1-h time-weighted average was 481 ppm. These CO levels would cause mild headache, fatigue, nausea and dizziness (OSHA, WHO) (WHO 2011).

In the half open door position, the overall time-weighted-average (TWA) CO concentration for the entire experiment (2 h) at 150 cm was 28 ppm. According to WHO and OSHA, this level would not cause any immediate symptoms. However, the 1-h TWA was 47 ppm which is lower than the dangerous levels set by UK-EU-WHO-OSHA (WHO 2011) for 60-min CO exposures. In the sitting position height (at 30 cm), the 2-h TWA was 25ppm. However, the 1-h TWA was 37 ppm which is higher than the 25 ppm level set by UK-EU-WHO-OSHA (WHO 2011) for 60-min CO exposures.

In the fully open-door position, the overall time-weighted-average (TWA) CO concentration for the entire experiment (110 min) at 150 cm was 22 ppm-TWA. According to WHO and OSHA, this

**Table 6.** CO concentrations and Kidde alarm response times (Kidde-United-Technologies 2018).

Carbon Monoxide Level	Alarm Response Time
40 ppm	10 h
50 ppm	8 h
70 ppm	1 to 4 h
150 ppm	10 to 50 min
400 ppm	4 to 15 min

level would not cause any immediate symptoms. However, the 1-h TWA was 30 ppm which is lower than the dangerous levels set by UK-EU-WHO-OSHA (WHO 2011; Health and Safety Executive 2011) for 60-min CO exposures (set in 2011, and 2005). In the sitting position (at 30 cm), the overall TWA CO concentration was 17 ppm for the entire experiment (1 h 50 min). However, the 1-h TWA was 22 ppm which is lower than the levels set by UK-EU-WHO-OSHA (WHO 2011) for 60-min CO exposure. This CO level is also lower than the levels set by UK-EU-WHO-OSHA for the 60 min (set in 2015) CO exposures in the standing position. However, low levels of CO exposure have been linked neurodevelopment disorders (Levy 2015).

However, all the recorded CO values in this case study are higher than 20 ppm – long-term exposure (8 h) and the 100 ppm – short-term exposure (15 min) set by the UK Health and Safety Executive 2018 (Health and Safety Executive 2018).

## Conclusions

In this study, the emissions of CO from wood sawdust and charcoal from the same wood species were evaluated. Sawdust emitted less CO than charcoal. Secondary, a case study of CO accumulation in a confined space was simulated using an ISO container. CO emission from wood sawdust were in the range 98.8 mg/g as lowest to 258.0 mg/g as highest across all temperatures and airflows. On the other hand, the CO emission from charcoal were in the range 98.1 mg/g as lowest to 495 mg/g as highest across all temperatures and 186.6 mg/g as lowest to 426.8 mg/g as highest across all airflows. There was a general decrease in CO emissions across all temperatures and airflows for both sawdust and charcoal except wood sawdust for which the CO emissions from each sample was affected differently by temperature. The amounts of CO emissions recorded in the ISO container increased with decrease in airflow within the container. Higher amounts of CO were recorded at the upper parts of the container compared to the lower parts. This study clearly shows that both wood and charcoal produce dangerous amounts of CO which could become even more dangerous in confined spaces in case of aeration challenges.

## Highlights

- CO emissions were quantified from wood sawdust and charcoal
- Accumulation of CO in confined spaces was simulated using an ISO container
- Temperature and airflow both affected the emissions of CO
- CO emissions from sawdust were in the range 98.8 to 258.0 mg/g
- CO emissions from charcoal were in the range 98.1 to 495 mg/g
- CO emissions in the ISO container increased with decrease in aeration and distance above the container floor.

## Acknowledgments

The authors thank the Gas Safety Trust (UK), the Boat Safety Scheme (UK), Cranfield Forensic Institute (UK) and the Katie Haines memorial Trust (UK) for sponsoring this work. Gratitude for the experimental support provided by Adrian Mustey and Karl Norris.

## Funding

This work was supported by the Katie Haines Memorial trust, United Kingdom; Boat Safety Scheme, United Kingdom; Gas Safety Trust, United Kingdom.



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