



Dust and Gas Emissions from Small-Scale Peat Combustion

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ABSTRACT

While peatland has long been exploited for agricultural activities, these make it vulnerable to fires, which emit pollutants into the atmosphere and adversely affect air quality. The aim of this study was thus to determine the main composition of air pollutants from peat soil combustion. The main parameters of the related gas pollutants, e.g., SO₂, NO₂, CO, O₃ and PM₁₀, and their components, such as anions, cations, heavy metals and levoglucosan, have been determined. The gas concentration was determined using the colorimetric method after the air had been assimilated into absorbing solutions. The PM₁₀ concentration was established using a low volume air sampler equipped with weighted filter paper. The anion concentration of PM₁₀ was analyzed using ion chromatography, while the cation and heavy metal concentrations were ascertained using inductively couple plasma-mass spectroscopy (ICP-MS). Moreover, the concentration of levoglucosan was determined using the Anthrone-Sulfuric Colorimetric method. The results show that the dominant gas from the emission of burning peat soil was CO (13850–20610 µg/m³) followed by NO₂ (608–831 µg/m³), SO₂ (113–367 µg/m³) and O₃ (76–156 µg/m³). A high PM₁₀ concentration was released from 1 h peat soil combustion with a range of 778–3444 µg/m³. The composition of heavy metals in PM₁₀ shows the sequence of Zn > Al > Fe > Cr > Pb > Cu > Ni > Cd. The sequence of anion and cation concentrations in PM₁₀ was NO₃⁻ > SO₄²⁻ > Na⁺ > Cl⁻ > Ca²⁺ > K⁺ > F⁻ > Mg²⁺. Levoglucosan was found to be a good indicator for peat combustion at a range of 1.44–3.90 µmol/m³. This research shows that the emission of peat soil fires produces various amounts of air pollutants that affect the environment and chemical reactions in the atmosphere.

Keywords: Peatland fires; PM₁₀; Anion; Cation; Levoglucosan; Heavy metals; Gas.

INTRODUCTION

Peatlands, which are naturally waterlogged and rich in carbon, are continually being exploited, particularly for drainage activities in response to agricultural development (Silvius and Diemont, 2007; Hooijer *et al.*, 2010; Jaenicke *et al.*, 2010; Miettinen and Liew, 2010). However, the unsustainable use of peatlands leads to extensive land clearing activities, deforestation, and land degradation (van Beukering *et al.*, 2008; Ansari, 2011) which in turn lower the groundwater level and increase the risk of fire, particularly during the dry season (Wosten *et al.*, 2008). Peat fires tend to have a far greater impact on their surroundings, as they are difficult to manage and are prone to burn for long periods, even when there is extensive precipitation or human efforts to control them (Blake *et al.*, 2009; Grishin *et al.*, 2009). Peatland fires have been identified as a major source of smoke pollution with high

carbon emissions (Page *et al.*, 2002; Heil *et al.*, 2007; Tacconi *et al.*, 2007).

Peatland and biomass burning contribute significantly to forest fires in Southeast Asia (Heil *et al.*, 2007; Akagi *et al.*, 2011; Miettinen *et al.*, 2011), with biomass burning predominantly linked to land clearing activities, especially during harvesting season or in preparation for changing the use of land (Goldammer, 1993; Saharjo and Munoz, 2005; Murdiyarso and Lebel, 2007; Anwar *et al.*, 2010). Many studies have estimated the contribution of pollutants from biomass burning to the atmosphere (Crutzen and Andreae, 1990; Cooke *et al.*, 1996; Innes, 2000; Andreae and Merlet, 2001; Harrison *et al.*, 2009; Langmann *et al.*, 2009) and CO₂ and CO have been found to be the dominant elements released (Andreae and Merlet, 2001; Edwards *et al.*, 2004; Langmann *et al.*, 2009) while particulate matter is considered a predominant element (See *et al.*, 2007; Blake *et al.*, 2009). The main components of biomass burning emissions are fundamentally: water vapour, volatile organic compounds, hydrocarbon, particles, NH₃ (Andreae and Merlet, 2001; Goldammer *et al.*, 2009), N₂O, CH₄, NO_x, SO_x, (Itkonen and Jantunen, 1983; Hadi *et al.*, 2000; Blake *et al.*, 2009) and trace gases (Robinson, 1991; Beringer *et al.*, 1995; Ramadan *et al.*, 2000; Gebhar *et al.*, 2001; Stephen and Low, 2002; Yokelson

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et al., 2008). Biomass burning smoke itself is composed of sulfur, potassium, polycyclic aromatic hydrocarbon (PAH) (Blake *et al.*, 2009), Na, Mn, Ca, Si, F, Cl, Ti, Fe, Zn and Pb which is usually absorbed into the surface of particulate matter (Reh and Deitchman, 1992; Muraleedharan *et al.*, 2000a; Ward and Smith, 2001; Radojevic, 2003; Goldammer, 2007). These emissions significantly disturb the chemical composition of the atmosphere (Lapina *et al.*, 2006; Urbanski *et al.*, 2009).

Air pollutants from peat combustion contribute to transboundary air pollution in the Southeast Asia region (Heil *et al.*, 2007). This is often connected to El Niño/Southern Oscillation (ENSO) events (Matsueda *et al.*, 2002; Tacconi, 2003; Goldammer, 2007). There are several consequences of biomass burning emissions, such as light-scattering and absorption effects, along with the occurrence of black carbon (Wardoyo *et al.*, 2011; Portin *et al.*, 2012) which causes episodic haze, reduced visibility and adverse health effects (Tacconi *et al.*, 2007). The low intensity of sunlight during haze increases the distribution of harmful bacteria and viruses that should have been killed by ultraviolet B (Beardsley *et al.*, 1997; Afroz *et al.*, 2003). According to Muraleedharan *et al.* (2000a) many Southeast Asian haze episodes, such as those recorded in 1983, 1990, 1991, 1994, 1997 and 1998, have resulted in negative health effects on a large population. Suspended particles from haze in particular can impact human health in a number of ways, leading to conditions such as upper respiratory tract infection, asthma, and conjunctivitis (Awang *et al.*, 2000). In addition, the release of organic pollutants from biomass burning, such as PAH which is carcinogenic, can lead to a high risk of cancer (Tullin *et al.*, 2001; Silva *et al.*, 2010).

As emissions of air pollutants in Southeast Asia are usually triggered by biomass burning in peat soil areas, this study aims to investigate the emissions of major air pollutants from small-scale peat combustion using a simple-design open oven. The main parameter of gas pollutants, such as CO, SO₂, NO₂, and O₃, was determined. Moreover, this study will also quantify the amount of PM₁₀ and its composition, in order to characterize and determine the possible pollutants emitted from peat soil combustion.

MATERIALS AND METHODS

Sampling Sites

Samples of peat soil were taken three times from each location between October 2011 and February 2012. The sample sites were located in two peat-dominant forest areas situated in the Kuala Langat Utara and Kuala Langat Selatan Forest Reserve (Fig. 1). Eight sampling stations (S1–S8) were chosen within these sampling areas in order to determine the distribution of peat soil and its composition (Table 1). Malaysian peatlands are predominantly located behind mangrove coastlines (Wetland International, 2010). This richly organic soil area has been exploited for cultivation and for agricultural activities, thus leading to a reduction of such peaty areas in Malaysia. The two sampling areas selected are, in fact, among the few such areas remaining in Selangor, Malaysia.

Soil Sampling

Surface soil samples were collected using plastic shovels, as described by Tahir *et al.* (2007). Samples were stored in ziplock plastic bags and then dried through sun exposure before further analysis. Soil moisture content was determined by drying the soil samples in an oven for 24 h, as described by Alves *et al.* (2010), and was recorded between 50–80%. The combustion of peat soil was conducted in a simple-design oven (Fig. 2), a metal container designed to just combust the soil, without any control of airflow. This combustion technique reflects the main condition of peat being burned by farmers at the sampling areas after land-clearing activities. The small burning oven (40 cm diameter) used to combust the peat soil was modified from a design by Muraleedharan *et al.* (2000b), with an open burning technique, in order to investigate the emissions from peat combustion. About 0.5 kg of dried peat soil was compacted into a square cubic shape (0.15 × 0.15 × 0.05 m) and then combusted at around 300°C. The emissions from the combustion were expelled through a small opening at the top of the oven. This burning procedure was used for both the ignition and smoldering phases.

Sampling of PM₁₀

Concentration of PM₁₀ was measured using a MiniVol portable air sampler (Airmetrics) equipped with Pallflex membrane filters (47 mm diameter, 0.47 µm pore size) with a flow rate of 5 L/min for 1 h (Norela *et al.*, 2005; Latif *et al.*, 2006; Sang *et al.*, 2011). The air sampler was placed 0.3 m from the burning oven. Each piece of filter paper was stored in a desiccator for 48 h before and after sampling, and prior to being weighed. The concentration of PM₁₀ was determined by measuring weight differences in the filter paper before and after sampling, in accordance with the volume of air absorbed by the air sampler. An instrument blank was obtained through placing the filter paper in the sampler for 1 h without switching it on.

The extraction of filter paper for determination of anion, cation and levoglucosan concentration was undertaken by diluting half of the exposed filter paper, which was cut into small pieces (1 cm²) using a clean pair of scissors, with 100 mL deionized water in a 250 mL conical flask. The filter paper was then digested in a water bath for 2 h and sonicated for 15 min in order to ensure that all the soluble matter had been diluted in the deionized water (Latif *et al.*, 2006). The remaining sample was then filtered using a filter pump with Sartorius Stedim cellulose acetate filter paper (47 mm diameter, 0.2 µm pore size) and diluted with 250 mL deionized water before being stored in a bottle at 4°C until analysis.

The extraction of the heavy metal from the filter paper was undertaken using half of the filter paper, which was digested with nitric acid and perchloric acid at a ratio of 3:2 using a hot plate, as described by Latif *et al.* (2006). Then, another 50 mL nitric acid was added to the solution to ensure complete digestion. After this, the sample was cooled before being filtered using a filter apparatus with Whatman GFC filter paper (47 mm diameter, 0.45 µm pore size) and diluted with 250 mL deionized water. The sample was then stored in a plastic bottle at 4°C before further analysis.

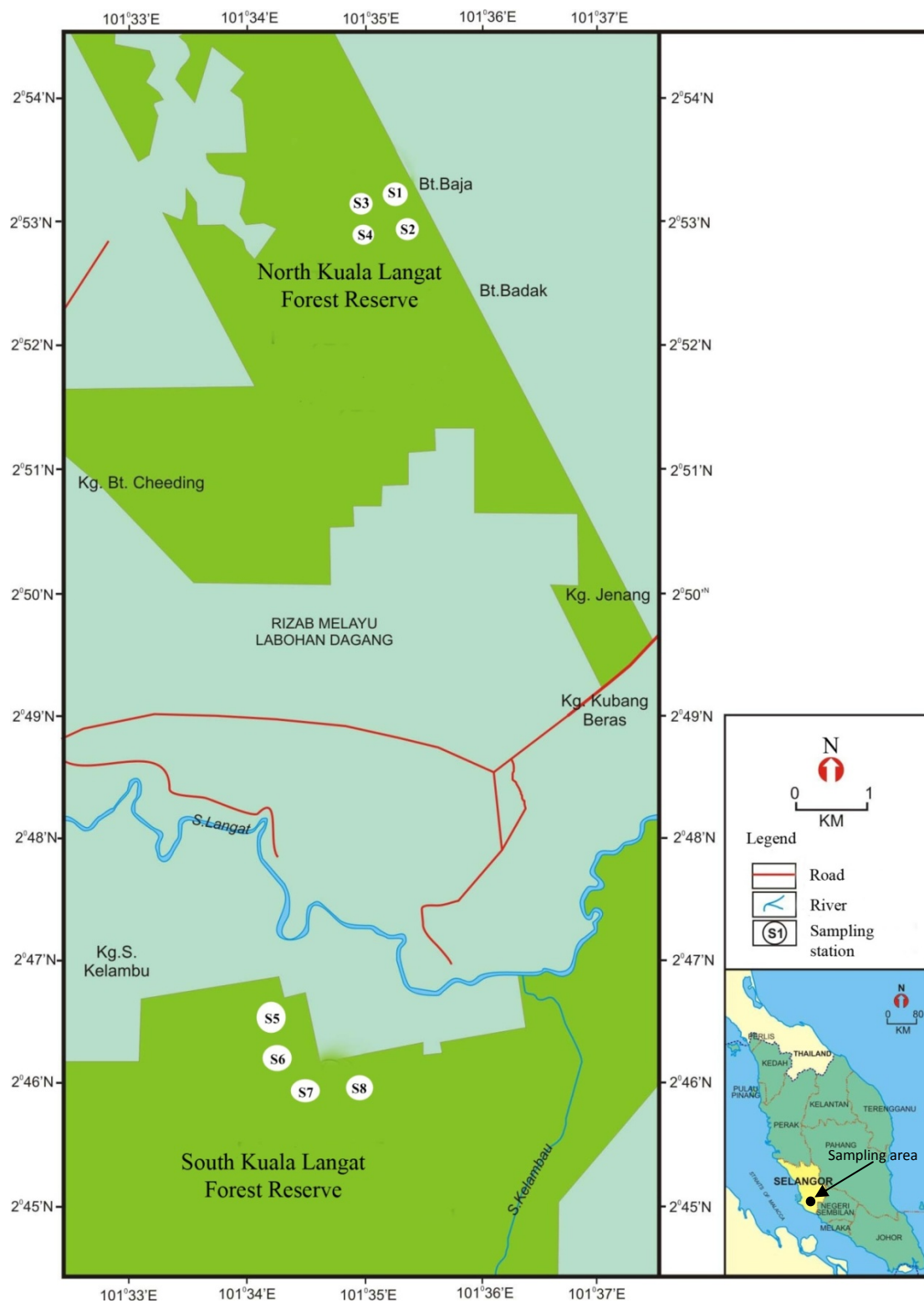


Fig. 1. Sampling locations for peat soils in peat swamp forest.

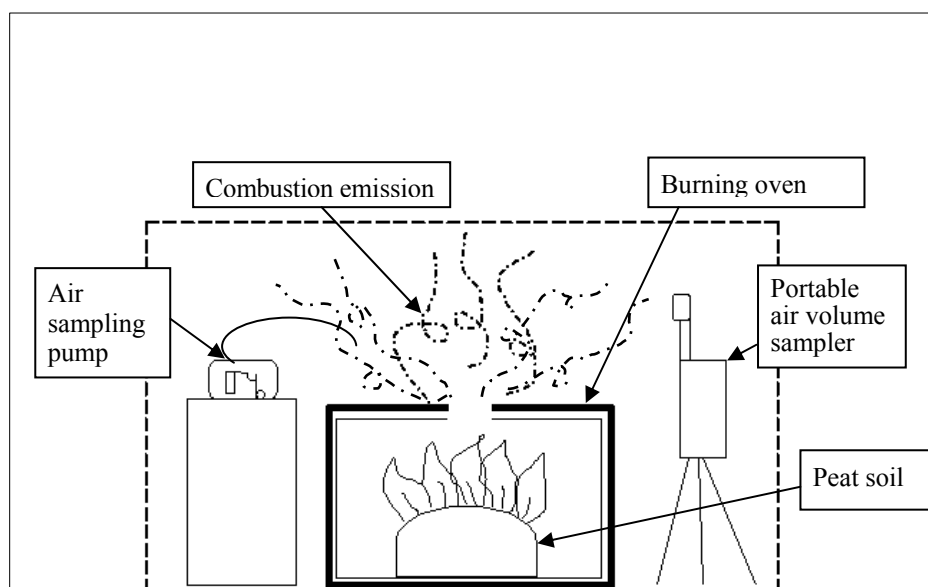
Determination of Levoglucosan in PM_{10}

Levoglucosan concentration in the peat combustion emission was determined by using the anthrone-sulfuric colorimetric method, as described by Fartas *et al.* (2009) and Latif *et al.* (2011). When using this method, a standard calibration curve needs to be produced (0.1–1.0 mM) through

the preparation of an anthrone standard solution, which is 0.194 g anthrone (9, 10-dihydro-9-oxoanthracene) diluted with 1 L of deionized water. This solution was analyzed using a UV Spectrometer at a wavelength of 620 nm. Next, the anthrone reagent was prepared by dissolving 0.2 g anthrone with 100 mL sulfuric acid 97% in a 250 mL conical flask

Table 1. Location of peat soil sampling stations.

Stations	Latitude	Longitude	Area description
S1	02°53'24"	101°35'49"	Forest
S2	02°53'21"	101°35'49"	Forest
S3	02°53'24"	101°35'40"	Forest
S4	02°53'21"	101°35'47"	Forest
S5	02°46'56"	101°34'56"	Forest
S6	02°46'42"	101°34'56"	Forest
S7	02°46'04"	101°34'33"	Agricultural
S8	02°46'06"	101°34'47"	Agricultural

**Fig. 2.** Schematic diagramme for peat combustion analysis.

for 45 min. This reagent was prepared just before being used (Laurentin and Edwards, 2003). Next, 10 mL of anthrone reagent was pipetted into a thick-walled Pyrex tube with 5 mL of the sample. This was then immersed into a water bath at 100°C for 10 min, followed by 5 min in both 4°C and 20°C water to prevent condensation on the tube, which could disturb the reading process. The sample was then analyzed using a UV spectrometer with a 620 nm wavelength against the 0.1 mM standard solution as a blank, and the levoglucosan concentration was determined by comparing it with the standard calibration curve. The lowest detection limit for levoglucosan is 7 μ M.

Anion, Cation and Heavy Metals in PM_{10}

Anions (F^- , Cl^- , NO_3^- , SO_4^{2-}) were analyzed using ion chromatography (Metrohm 850 IC Plus) with a detection limit of 0.23 ng/m^3 for F^- , 0.4 ng/m^3 for Cl^- , 0.27 ng/m^3 for NO_3^- , and 0.77 ng/m^3 for SO_4^{2-} . Cations (Na^+ , Mg^{2+} , Ca^{2+} , K^+) and heavy metals (Cd, Cu, Zn, Fe, Al, Pb, Cr, Ni) were analyzed using inductively coupled plasma-mass spectroscopy (ICP-MS) (PerkinElmer Elan 9000) with a detection limit 0.07 ng/m^3 for K^+ , 0.1 ng/m^3 for Mg^{2+} , 0.1 ng/m^3 for Na^+ , 0.07 ng/m^3 for Ca^{2+} , 0.03 ng/m^3 for Cd, 0.07 ng/m^3 for Cu, 0.1 ng/m^3 for Zn, 0.1 ng/m^3 for Fe, 1.67 ng/m^3 for Al, 0.17 ng/m^3 for Pb, 0.07 ng/m^3 for Cr, and 0.13 ng/m^3 for Ni.

The standard solutions were prepared by diluting the stock solution of 1000 mg/L with ultrapure water in a volumetric flask.

Peat Soil Composition

The concentration of anions and cations in the soil sample were analysed before and after combustion in order to determine any significant alterations in the soil properties as a result of combustion. A 50 mg soil sample was sieved using a 63 μ m sieve and extracted with 50 mL deionized water, then sonicated for 1 h for anion and cations analyses. The heavy metal concentrations in the soil were determined using USEPA Method 3050B Acid Digestion of Sediments, Sludges, and Soils. The filtered samples were then analyzed using ion chromatography for the anions, while cations and heavy metals were analyzed using ICP-MS.

Concentration of Gases during Emission

The concentration of emitted gases (SO_2 , NO_2 , CO, and O_3) from peat combustion was determined through the use of a LaMotte air sampling pump, based on the colorimetric method (McDermoff, 2004), after the air was absorbed into the absorption solution at a 1 L/min flow rate for each of the gases for 1 h. The air was absorbed into the absorbing solutions for particular gases, as introduced by LaMotte

Chemicals, and the transmission was measured with a UV spectrometer. The concentration of each gas was determined by comparing the transmission value with the calibration chart provided by LaMotte Chemicals.

Calculation of Emission Factor

There are several calculations for emission factor (g/kg) and the majority of them require data on the carbon contained in the burning materials and the carbon budget of the fire as stated by Ward and Radke (1993), Andreae and Merlet (2001), Koppmann *et al.* (2005), Akagi *et al.* (2011) and Yokelson *et al.* (2011). According to Lemieux *et al.* (2004) and Oanh *et al.* (2011), the emission factor from the combustion of materials through laboratory measurements can be calculated based on the actual dried mass density using Eq. (1):

$$\text{Emission factor} : \frac{(C_{\text{sample}}) \times Q \times t}{M_{\text{burned}}} \quad (1)$$

where C_{sample} is the concentration of the pollutant (g/m^3), Q is the flow rate of dilution air (m^3/min), t is the sampling time and M_{burned} refers to the dried mass burned (kg).

Statistical Analysis

The data obtained from this research was tested using a normal P-P plot, normal Q-Q plot, and one-sample Kolmogorov-Smirnov test in order to indicate the normality of the data. In addition, the correlation coefficient and correlation significance were analyzed using a one-way ANOVA and t-test with the application of the Statistical Package for Social Science (SPSS version 19) to determine the significant difference among the mean concentrations of anions, cations, heavy metals, and levoglucosan.

Quality Control

To avoid the experiment being influenced by the ambient air surrounding the area, the burning process was conducted in semi-closed area in a laboratory compound. The location of the burning area, with respect to the location of buildings around the compound, was considered to have a low level of anthropogenic pollutants. The concentration of PM_{10} without any combustion activity for 1 h is below $10 \mu\text{g}/\text{m}^3$. The concentration of gases determined in ambient air were almost undetected, except for O_3 ($14 \mu\text{g}/\text{m}^3$) and NO_2 ($47 \mu\text{g}/\text{m}^3$).

Before the samples were analyzed, all glassware and polyethylene bottles were soaked in a 20% nitric acid bath for 24 h before being rinsed with ultra pure water with a resistivity of 18.2 M Ω m. Fresh deionized water and ultra pure water were used during lab work each day to retain the resistivity of the water. Blank sample filter paper was also analyzed in the same manner as the sample in order to eliminate any possible source of contamination during sampling and analysis. To verify the accuracy of the method and analytical procedures, recovery tests were undertaken with known concentrations of standard solutions. The standard solutions were treated with the same procedure as the samples, with percentage of recoveries between 55 and

168%.

RESULTS AND DISCUSSION

Emission from Peat Combustion

The concentrations of PM_{10} and gases for a 1 h average time are shown in Table 2. Overall, CO was the dominant gas produced from peat combustion, with a concentration of 13850–20610 $\mu\text{g}/\text{m}^3$. Other gases showed an average concentration far lower than that, with ranges of 608–831 $\mu\text{g}/\text{m}^3$ for NO_2 , 113–367 $\mu\text{g}/\text{m}^3$ for SO_2 , and 76–156 $\mu\text{g}/\text{m}^3$ for O_3 . The average PM_{10} concentration from peat combustion was found to be $2283 \pm 2005 \mu\text{g}/\text{m}^3$, with a range of 778–3444 $\mu\text{g}/\text{m}^3$. No significant differences ($p > 0.05$) were found for any of the gases or PM_{10} as recorded from the samples collected from the different stations. Variations and incomplete combustion processes of peat soils, along with different composition, were expected to contribute to the varying levels of gases and PM_{10} obtained from the samples collected from the same station. The distribution of gases was better distributed compared to the amount of particulate matter that led to the high variability of PM_{10} compared to that of gases.

The high concentration of CO among the gases may be due to the characteristics of peatland areas, which are highly rich in carbon. According to Gorham (1991), peat areas can store large amounts of carbon via the production and accumulation of plant materials. Moreover, CO is produced during the combustion of carbonic materials such as peat soil with a minimum oxygen supply (Braunstein *et al.*, 1981), as shown in Eq. (2):



The emission of CO resulted from a low combustion temperature and insufficient supply of O_2 ; fuel was not well mixed with air and the residence time of the combustion gases was too short (Eskilson *et al.*, 2004; Gonzalez *et al.*, 2004; Ozil *et al.*, 2009; Tissari *et al.*, 2009; Roy and Corscadden, 2012). Studies by Gupta *et al.* (2001), Edward *et al.* (2004) and Koppmann *et al.* (2005) reported that incomplete combustion from forest fires produces a high quantity of CO. According to Andreae and Marlet (2001), the reaction between oxygen and carbon from the char on the fuel materials during the flaming and smoldering phases produces CO at a low temperature of $< 577^\circ\text{C}$. NO_2 was found to be the second highest concentration during emission. The quantity of NO_2 that can be emitted from peat soil corresponds to the level of nitrogen. According to Moore and Bellamy (1974), nitrogen is the major component of plant and animal tissue that accumulates in peat. During combustion, when the fuel was heating up, NH_3 and HCN were released from the fuel, and its tar. These were then oxidized to form NO (Winter *et al.*, 1999). NO, which is a nitrogen species emission during combustion, was later oxidized to NO_2 (Andreae and Merlet, 2001). Jaffe and Wigder (2012) reported that peat containing a high level of nitrogen produces high NO_x (NO and NO_2) emission during combustion. The stages of combustion, air ratio, and

Table 2. Concentration of PM₁₀ and gases for 1 h sampling duration.

Stations	PM ₁₀	SO ₂	NO ₂ (µg/m ³)	CO	O ₃
S1	2222 ± 2988	135 ± 85	831 ± 304	16240 ± 4020	106 ± 42
S2	2000 ± 1000	113 ± 25	831 ± 385	13850 ± 4900	114 ± 42
S3	2000 ± 1155	178 ± 90	729 ± 20.3	14540 ± 2810	76 ± 21
S4	3111 ± 3672	127 ± 5	689 ± 81	14200 ± 7720	84 ± 17
S5	3111 ± 1836	189 ± 28	750 ± 365	20100 ± 13700	114 ± 21
S6	778 ± 770	169 ± 17	608 ± 284	20610 ± 9050	148 ± 63
S7	3444 ± 4286	333 ± 11	634 ± 304	20610 ± 9050	156 ± 84
S8	1600 ± 1102	367 ± 23	628 ± 203	19590 ± 4460	114 ± 42
Average	2283 ± 2005	201 ± 36	712 ± 243	17468 ± 6963	114 ± 42

Note: The average calculation is based on the overall results.

temperature also determine the amount of NO₂ produced from peat combustion (Kubica *et al.*, 2007). A low concentration of SO₂ compared with other gases is most likely to be due to the low sulfur content of the peat soils. In addition, the direct emission of peat combustion does not contribute to the high amount of secondary pollutants, such as O₃, due to the characterization of O₃ formation, which requires certain exposure to UVB radiation. Ozone itself can only be formed in the presence of sunlight radiation (Jaffe and Wigder, 2012). The high CO concentrations (compared with NO₂, SO₂, and O₃) in this study are consistent with studies by Andreae and Merlet (2001) and Hamada *et al.* (2010) which also found high gas concentrations, particularly CO, during tropical and peatland forest fires. This high C-containing product resulted from incomplete oxidation combustion.

The anions, cations and heavy metals concentrations in the peat soil were analysed both before and after combustion. Several anion, cation and heavy metals elements (SO₄²⁻, Cl⁻, Zn, Ni, Cu, Cr, Al and Pb) recorded slightly higher concentrations after peat combustion (Figs. 3 and 4). According to Saharjo (2007), combustion and fire can significantly affect the chemical and physical properties of soil which are dependent on the type of the soil, moisture content, intensity and duration of the fire. The results were also influenced by ash, which contains a high level of minerals, being produced following burning. A higher soil fertility and nutrient content after combustion were due to the low intensity of the fire (Ilstedt *et al.*, 2003). Based on the total amount of anions, cations, and heavy metals, which were recorded as around 20% of PM₁₀, the amount of carbon is expected to dominate the concentration of PM₁₀. According to Saharjo (2007), the quantity of carbon contained in peat soil is around 50–55%. Another study, by Satrio *et al.* (2007), indicated that the tropical peat swamp forest had an extremely acidic environment (pH 3.737) and that a large amounts of total carbon (48.823%), low mineral nitrogen (0.896%), and high C/N ratio (58.427%).

Emission Factor from Peat Combustion Emission

Many studies have estimated the emission factor through the use of several types of fuel and combustion techniques, such as vegetation combustion using a modified stove (Wardoyo *et al.*, 2011), canister combustion using an exhaust stack facility (Christian *et al.*, 2004), vegetation from forest

combustion using a burn chamber with an exhaust stack (Warneke *et al.*, 2011), municipal solid waste combustion using an electrically heated tube furnace (Tang *et al.*, 2012) and coal and wood combustion using a household stove (Zhang *et al.*, 2012). The emission factor value for PM₁₀ and gases (SO₂, NO₂, CO, O₃) during peat combustion in this study compared to other studies is shown in Table 3. Overall, the highest emission factor value in this study was CO (0.01 g/kg) followed by PM₁₀ (1.3E⁻³ g/kg), NO₂ (4.0E⁻⁴ g/kg) and SO₂ (1.1E⁻⁴ g/kg) while O₃ had the lowest and somewhat negligible emission factor.

The highest emission factor value of CO in this study is consistent with other findings but it is still low when compared to Kadam *et al.* (1999), Zhang *et al.* (1999), Andreae and Merlet (2001), Lemieux *et al.* (2004), Akagi *et al.* (2011), Oanh *et al.* (2011), Yokelson *et al.* (2011), Franca *et al.* (2012) and Yu *et al.* (2012) for various combustion techniques employed for vegetation and garbage. The low emission factor value in this study is due to the open burning combustion technique and slow combustion process. According to Zhang *et al.* (1999) and Ottmar *et al.* (2009), the emission factor value depends on the type and arrangement of fuel, as well as combustion efficiency during the combustion phase. The combustion phase dramatically affects emission because the primarily smoldering phase produces a higher amount of pollutants (Ottmar *et al.*, 2009).

Composition of PM₁₀ from Peat Combustion

Anions and Cations

The concentrations of anions and cations in PM₁₀ are shown in Table 4. NO₃⁻ had the highest average concentration of both anions and cations, with a concentration of 217 ± 82.0 µg/m³. In addition, SO₄²⁻ had the second-highest concentration of anions, with an average concentration of 50.7 ± 11.9 µg/m³, followed by Cl⁻ and F⁻, with average concentrations of 33.6 ± 22.3 µg/m³ and 4.9 ± 1.7 µg/m³, respectively. Na⁺ showed the highest concentration of cations, with an average concentration of 46.2 ± 37.1 µg/m³, followed by Ca²⁺ (13.1 ± 8.3 µg/m³), K⁺ (12.5 ± 6.4 µg/m³), and Mg²⁺ (1.3 ± 0.6 µg/m³), respectively. The overall sequence of anion and cation concentrations is NO₃⁻ > SO₄²⁻ > Na⁺ > Cl⁻ > Ca²⁺ > K⁺ > F⁻ > Mg²⁺. The results of the one-way ANOVA show no significant differences (p > 0.05) between anion and cation concentrations in PM₁₀ from the combustion

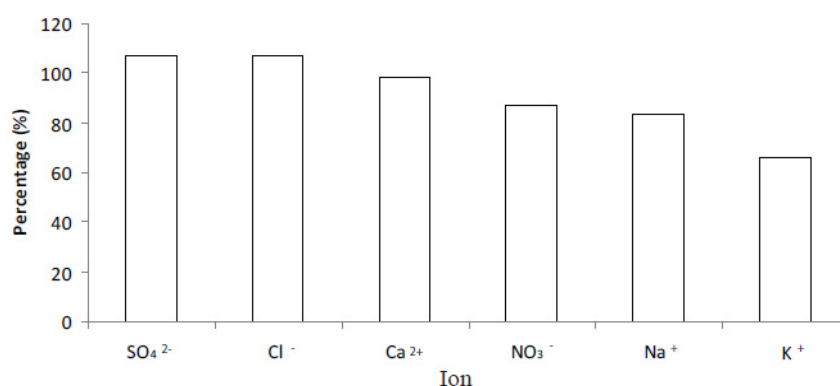


Fig. 3. Percentage of ions after peat combustion.

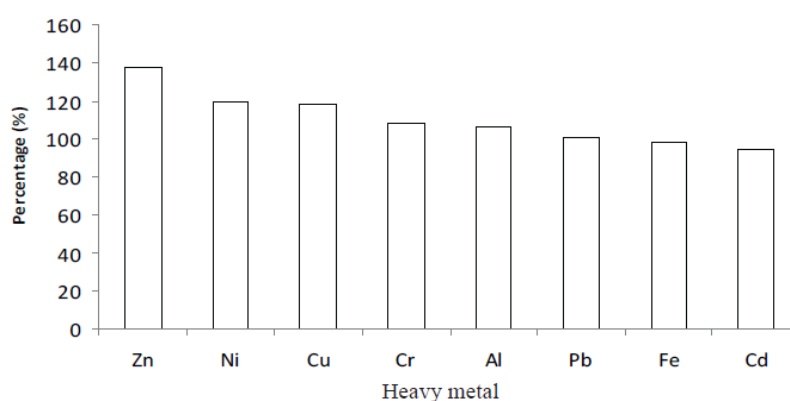


Fig. 4. Percentage of heavy metals after peat combustion.

Table 3. Emission factors during peat combustion emissions with comparisons from other research.

References	Types of biomass burning	PM ₁₀	SO ₂	NO ₂	CO	O ₃
		(g/kg)				
Zhang <i>et al.</i> (1999)	Plant residue	nd	nd	nd	77	nd
Kadam <i>et al.</i> (2000)	Rice straw	3.7	nd	3.10	34.7	nd
Andreae and Merlet (2001)	Tropical forest	104	0.57	nd	104	nd
Lemieux <i>et al.</i> (2004)	Agricultural	11	nd	nd	58	nd
Akagi <i>et al.</i> (2011)	Plant residue	nd	nd	3.11	102	nd
Oanh <i>et al.</i> (2011)	Rice straw	9.4	nd	nd	97	nd
Yokelson <i>et al.</i> (2011)	Garbage	nd	nd	6.87	41.46	nd
Franca <i>et al.</i> (2012)	Sugarcane	nd	nd	1.5	65	nd
Yu <i>et al.</i> (2012)	Rice straw	6.28	0.058	nd	30.30	nd
This study	Peat soil	$1.3 \times E^{-3}$	$1.2 \times E^{-4}$	$4 \times E^{-4}$	0.1	$6 \times E^{-4}$

nd: no data

of peat collected at each station. This result suggests that the composition of peat is quite uniform, even though samples were collected from different areas.

NO₃⁻ recorded the highest concentration of all the ions in PM₁₀ from peat soil combustion. Significant quantities of N and NH₄⁺, which are fixed in the biomass peat (Daniels *et al.*, 2012), have the ability to be converted into NO₃⁻ through bacterial nitrification and oxidation processes during combustion (Jauhiainen *et al.*, 2012). The high SO₄²⁻ concentration in the sampling areas may be due to the use of pesticides, which leads to the slow accumulation of sulfur in peat soil. See *et al.* (2007) reported that during peat

combustion, SO₄²⁻ and NO₃⁻ were the most abundant ions in peat soil. These originate from sulfurous and nitrogenous materials, and they are converted into these ions via gas-to-particle conversion. The high Na⁺ concentration determined among cations may be the result of a high level of Na⁺ salt in plant materials, originating from rock minerals. The location of the peatland, which is situated behind a mangrove area, also contributes to a certain amount of sea salt being present in the peatland areas. Moore and Bellamy (1974) reported that the ionic component in peat soil is naturally produced from the weathering process and infiltration within the soil medium accompanied by other sources, such as precipitation,

Table 4. Concentration of anions and cations in PM₁₀ during the emission of peat combustion.

Stations	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺	Mg ²⁺	K ⁺	Ca ²⁺
	(µg/m ³)							
S1	3.2 ± 0.2	46.3 ± 23.0	91.4 ± 44.5	57.7 ± 11.3	50.7 ± 33.2	1.1 ± 0.1	9.8 ± 4.3	16.3 ± 14.6
S2	2.6 ± 1.1	32.0 ± 16.6	182 ± 126	46.2 ± 10.1	33.1 ± 29.4	1.5 ± 0.4	9.3 ± 7.5	7.40 ± 4.8
S3	2.8 ± 0.8	47.8 ± 21.3	281 ± 52.3	49.5 ± 6.7	45.6 ± 39.2	0.9 ± 0.7	7.9 ± 8.7	6.60 ± 5.4
S4	2.5 ± 1.0	41.0 ± 10.1	125 ± 157	53.2 ± 3.4	35.5 ± 25.3	0.9 ± 0.6	3.6 ± 4.4	5.80 ± 3.4
S5	4.5 ± 3.1	40.3 ± 47.6	288 ± 138	50.4 ± 20.9	60.7 ± 71.7	1.4 ± 1.1	24.8 ± 18.3	16.9 ± 14.1
S6	8.9 ± 3.5	29.9 ± 30.1	178 ± 52.8	32.5 ± 19.6	60.4 ± 44.1	1.3 ± 0.9	14.8 ± 2.0	14.7 ± 10.6
S7	8.5 ± 3.6	22.1 ± 24.8	328 ± 109	55.5 ± 18.1	51.6 ± 47.7	1.6 ± 1.0	15.6 ± 5.8	17.1 ± 8.0
S8	6.0 ± 0.3	9.44 ± 5.1	260 ± 21.0	60.7 ± 4.8	31.8 ± 5.85	1.8 ± 0.3	14.3 ± 0.8	19.6 ± 5.1
Average	4.9 ± 1.7	33.6 ± 22.3	217 ± 82.0	50.7 ± 11.9	46.2 ± 37.1	1.3 ± 0.6	12.5 ± 6.4	13.1 ± 8.3

dust, wind that transports minerals and soil particles and sea spray.

A Pearson correlation matrix was performed in order to evaluate the relationship among research results (Garcia and Millan, 1998; Al-Khashman and Shawabkeh, 2006; Shimamura *et al.*, 2007; Özsoy and Örnektekin, 2009). The outcomes of the Pearson correlation matrix for anion and cation concentrations during peat combustion in this study are shown in Table 5. There are strong correlations between Cl⁻ and Na⁺ ($r = 0.68$, $p < 0.01$), NO₃⁻ and K⁺ ($r = 0.53$, $p < 0.01$), and Ca²⁺ and Mg²⁺ ($r = 0.68$, $p < 0.01$). There are also good correlations between Ca²⁺ and SO₄²⁻ ($r = 0.44$, $p < 0.05$), K⁺ and Na⁺ ($r = 0.47$, $p < 0.05$), and Mg²⁺ and Cl⁻ ($r = -0.404$, $p < 0.05$). The existence of a strong correlation between Cl⁻ and Na⁺ suggests that these elements originated from the same source, namely, the sea spray that is spread by wind action to the sampling area. The negative correlation between Cl⁻ and Mg²⁺ suggests that high Cl⁻ will cause a lower Mg²⁺ concentration. The correlation between NO₃⁻ and K⁺ suggests that the source of these elements, which affect each other, was formed during peat combustion. According to Livbjerg (2001), biomass such as straw from vegetation rich in K⁺ can be dispersed into the environment through combustion, while Quiterio *et al.* (2004) and Xu *et al.* (2012) stated that a high level of K⁺, especially during dry periods, was contributed to by biomass burning.

Heavy Metals

The concentrations of heavy metals (Cd, Cu, Zn, Fe, Al, Pb, Cr, Ni) in PM₁₀ are shown in Table 6. The dominant metal was found to be Zn, with a concentration range of

33.65–38.21 µg/m³, followed by Al and Fe, which had average concentrations 1.3 and 2.3 times lower, respectively, than Zn. Moreover, other metals had low concentrations, with 0.02% Cd, 0.8% Cu, 2.2% Cr, and 0.3% Ni, compared to the overall concentration. The overall sequence of heavy metals concentration in PM₁₀ is Zn > Al > Fe > Cr > Pb > Cu > Ni > Cd. The variance of the heavy metals may due to the composition of peat soil and characteristic of the combustion. The one-way ANOVA shows no significant differences ($p > 0.05$) between heavy metal concentrations in PM₁₀ from the combustion of peat collected at the different stations.

A high Zn concentration in PM₁₀ may due to the concentration of Zn that was accumulated in the peat soil around the sampling area. The characteristics of peat soil, which is acidic with a high specific surface area, influences its capability to be a natural adsorbent (Kyziol, 2002). According to Shotyk (1996) and Smieja-Krol *et al.* (2010), peatland ecosystems with wet conditions can absorb atmospheric pollutants. Moreover, a high Zn concentration can be contributed to by particulate matter from urban areas (Shah *et al.*, 2012) and industrial processes (Barona and Romero, 1996; Akhlaghi and Kompany-Zareh, 2005). The high Zn concentration during peat fire was not consistent with results from a study by See *et al.* (2007) which indicated Al as the highest metals concentration in PM₁₀ from peat fire emissions. The high levels of Al and Fe found in this study suggest that these elements originate from crustal material. The presence of such high levels of Al and Fe may also be due to their natural composition in the soil and earth crust. According to Tan (1994), Al and Fe are important

Table 5. Correlation matrix for anions and cations in PM₁₀.

	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺	Mg ²⁺	K ⁺	Ca ²⁺
F ⁻	1							
Cl ⁻	0.001	1						
NO ₃ ⁻	0.31	-0.127	1					
SO ₄ ²⁻	-0.005	-0.176	0.173	1				
Na ⁺	0.379	0.709**	0.038	-0.319	1			
Mg ²⁺	0.098	-0.404*	0.156	0.347	-0.206	1		
K ⁺	0.325	0.250	0.527**	-0.228	0.468*	0.138	1	
Ca ²⁺	0.182	-0.340	-0.020	0.435*	-0.014	0.676**	0.088	1

*. Correlation is significant at the 0.05 level.

**. Correlation is significant at the 0.01 level.

Table 6. Concentration of heavy metals in PM₁₀.

Stations	Cd	Cu	Zn	Fe	Al	Pb	Cr	Ni
(µg/m ³)								
S1	0.02 ± 0.01	0.77 ± 0.43	38.2 ± 6.8	16.0 ± 5.21	22.5 ± 6.7	0.72 ± 0.44	2.25 ± 0.55	0.47 ± 0.44
S2	0.01 ± 0.00	0.34 ± 0.14	35.4 ± 11.1	17.9 ± 3.92	23.6 ± 2.9	0.35 ± 0.20	2.53 ± 0.40	0.20 ± 0.20
S3	0.02 ± 0.03	0.30 ± 0.22	33.7 ± 12.0	19.1 ± 9.52	26.3 ± 6.5	0.60 ± 0.74	2.50 ± 0.44	0.22 ± 0.20
S4	0.02 ± 0.00	0.41 ± 0.10	43.4 ± 2.60	19.4 ± 2.50	32.0 ± 7.4	0.67 ± 0.25	2.73 ± 0.47	0.21 ± 0.10
S5	0.03 ± 0.01	1.14 ± 0.42	37.4 ± 13.1	17.0 ± 6.27	29.6 ± 6.8	2.05 ± 0.70	1.25 ± 0.07	0.14 ± 0.08
S6	0.03 ± 0.02	0.90 ± 0.12	35.8 ± 13.1	13.5 ± 1.68	27.7 ± 8.6	1.46 ± 0.24	1.30 ± 0.03	0.67 ± 1.01
S7	0.03 ± 0.02	0.90 ± 0.25	35.6 ± 12.3	13.6 ± 1.33	28.1 ± 9.3	1.45 ± 0.13	1.40 ± 0.07	0.06 ± 0.02
S8	0.03 ± 0.02	0.78 ± 0.03	38.0 ± 14.1	13.9 ± 1.30	31.0 ± 10.8	1.50 ± 0.04	1.34 ± 0.10	0.09 ± 0.02
Average	0.02 ± 0.01	0.70 ± 0.21	37.2 ± 10.6	16.3 ± 3.97	27.6 ± 7.37	1.10 ± 0.34	1.90 ± 0.27	0.30 ± 0.26

elements and are most abundant in soil and the crustal surface.

Table 7 shows the Pearson correlation coefficients for heavy metals during the emission of peat combustion. The results show that there were strong relationships between Cu and Cd ($r = 0.66$, $p < 0.01$), Pb and Cd ($r = 0.66$, $p < 0.01$), Pb and Cu ($r = 0.85$, $p < 0.01$), Al and Zn ($r = 0.80$, $p < 0.01$), Cr and Fe ($r = 0.62$, $p < 0.01$), Cr and Cu ($r = -0.68$, $p < 0.01$), and Cr and Pb ($r = -0.71$, $p < 0.01$). The strong relationships between these metals are most likely due to the occurrences of these metals attributed to other metal concentrations, particularly during peat combustion. According to Shah *et al.* (2012), Cd, Pb and Zn are produced during burning and anthropogenic activities. A negative correlation for Cr with Cu and Pb suggests that higher levels of Cr lower the concentrations of Cu and Pb. There were also significant correlations between Fe and Zn ($r = 0.47$, $p < 0.05$) and Al and Fe ($r = 0.44$, $p < 0.05$), suggesting that the metals originated from the same source, namely, a crustal element.

Enrichment Factor of Heavy Metals during the Emission of Peat Combustion

The enrichment factor was calculated to gain further information on the sources of elements by a comparison with the most abundant elements in crustal materials (Al-Momani, 2003). According to See *et al.* (2007), Tahir *et al.* (2007), Murillo and Marin (2010), Cesari *et al.* (2012) and Xu *et al.* (2012), the enrichment factor is calculated through the equation described below (Eq. (3)):

$$EF = \frac{(M/Al)_{\text{aerosol}}}{(M/Al)_{\text{soil}}} \quad (3)$$

where $(M/Al)_{\text{aerosol}}$ refers to the concentration of an element and Al in the atmosphere, while $(M/Al)_{\text{soil}}$ refers to the concentration of the element and Al in the crustal element. An EF value approaching 1 suggests that the element originated from a crustal area, whereas a value in the $1 < EF < 10$ range indicates that it comes from a naturally occurring source and is not enriched. Moreover, a value of $10 < EF < 100$ suggests that the element was moderately enriched, while an EF value > 100 suggests that the element was highly enriched with anthropogenic activities as the main sources. Duan *et al.* (2006) asserted that the reference element must

have the characteristic of the most abundant element in the earth's crust, which is very stable and not affected by pollution and according to Al-Momani (2003), Al is the most common reference material in the earth's crust.

Fig. 5 shows the EF for heavy metals (Cd, Cu, Zn, Fe, Al, Pb, Cr, Ni) in PM₁₀. From the results it can be seen that Zn had the highest EF value (145) which verifies that this metal originated from biomass burning, specifically from peat combustion. Research by See *et al.* (2007) showed that Zn is one of the indicators of biomass burning and had a high EF value from peat soil combustion during a haze episode in Southeast Asia. On the other hand, Cd, Cu, Pb, Cr, and Ni had EF values larger than 10, suggesting that these elements were moderately enriched. This finding concurs with results from Duan *et al.* (2006), where high EF values were found for Cu, Pb, and Zn, thus indicating that these elements originated from a non-crustal element.

Levoglucosan

Levoglucosan analysis was undertaken to indicate the occurrence of biomass burning (Schkolnik and Rudich, 2006). The concentrations of levoglucosan in PM₁₀ are presented in Fig. 6. Overall, the average levoglucosan concentration in this study was 2.81 µmol/m³ proving that a trace of organic substance existed during peat soil combustion. High levoglucosan concentrations can be due to the presence of highly cellulose materials in the peat soil that undergo a pyrolysis reaction during combustion. According to Puxbaum *et al.* (2007), levoglucosan concentration can be influenced not only by the type of fuel, but also by combustion type. According to Simoneit *et al.* (1999) and Abas *et al.* (2004), the distribution and ratio of levoglucosan in smoke depend on heat intensity, aeration, and the duration of smoldering and flaming conditions. Moreover, levoglucosan tends to spread and be diluted when exposed to OH, thus reducing the initial concentration (Hoffmann *et al.*, 2010; Latif *et al.*, 2011). The results of the one-way ANOVA show no significant differences ($p > 0.05$) for levoglucosan concentrations in relation to sampling station.

A comparison between levoglucosan concentrations from this study and similar previous studies is shown in Table 8. The levoglucosan concentration in this study was found to be significantly higher when compared to results from dos Santos *et al.* (2002), Simpson *et al.* (2004), Puxbaum *et al.* (2007), Fartas *et al.* (2009), Sang *et al.* (2011) and Wagener

et al. (2012). The lower levoglucosan concentrations in the other studies are conceivable, due to the aerosol monitoring that was undertaken in the surrounding areas within 24 h; however, this study directly monitored the emissions from

peat combustion. Furthermore, a study by dos Santos *et al.* (2002) on sugarcane burning emissions showed that a lower levoglucosan concentration compared to the quantity of peat soil emissions.

Table 7. Correlation matrix for heavy metal concentrations in PM₁₀.

	Cd	Cu	Zn	Fe	Al	Pb	Cr	Ni
Cd	1							
Cu	0.660**	1						
Zn	-0.319	-0.044	1					
Fe	0.120	-0.109	0.467*	1				
Al	-0.132	-0.010	0.803**	0.442*	1			
Pb	0.662**	0.848**	0.178	0.047	0.325	1		
Cr	-0.389	-0.678**	0.197	0.622**	0.021	-0.711**	1	
Ni	0.394	0.172	-0.205	0.105	-0.218	-0.048	0.066	1

*. Correlation is significant at the 0.05 level.

**. Correlation is significant at the 0.01 level.

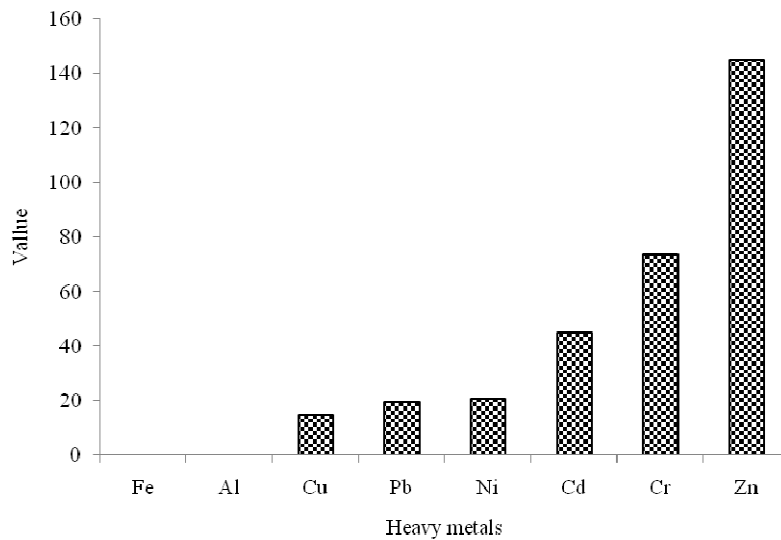


Fig. 5. Enrichment factor of heavy metals in PM₁₀.

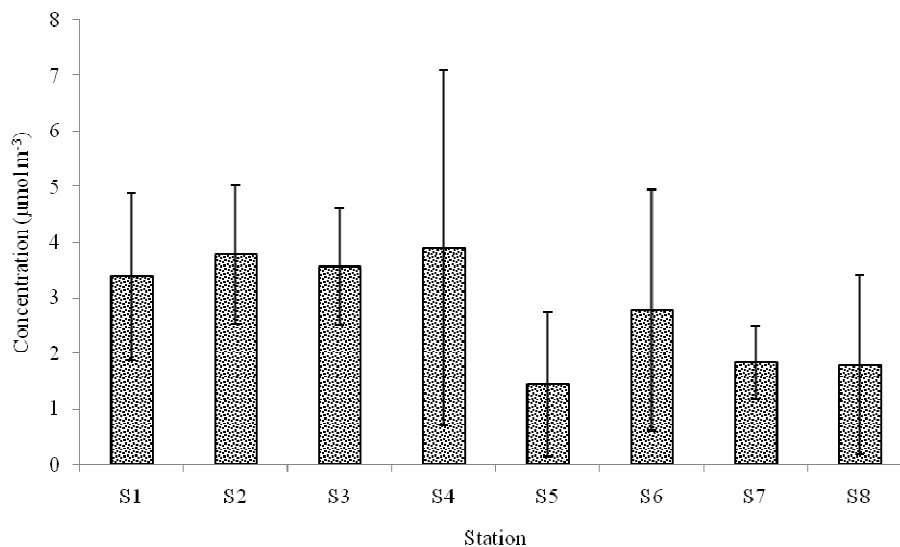


Fig. 6. Concentration of levoglucosan in PM₁₀.

Table 8. Summary of selected levoglucosan research compared to this current study.

References	Site	Levoglucosan ($\mu\text{g}/\text{m}^3$)
dos Santos <i>et al.</i> (2002)	Sugarcane combustion	0.16
Simpson <i>et al.</i> (2004)	Wood combustion	0.172
Puxbaum <i>et al.</i> (2007)	Coastal area	0.005
Fartas <i>et al.</i> (2009)	Semi-urban	0.24
Sang <i>et al.</i> (2011)	Urban	36
Wagener <i>et al.</i> (2012)	Urban	0.063
This research	Peat combustion	460

CONCLUSION

The results of this study show that there were high concentrations of particulate matter and gases emitted from peat soil combustion. Concentrations (1 h average) for PM_{10} and SO_2 , NO_2 , CO , and O_3 were $2283 \pm 2005 \mu\text{g}/\text{m}^3$, $201 \pm 36 \mu\text{g}/\text{m}^3$, $712 \pm 243 \mu\text{g}/\text{m}^3$, $17468 \pm 6963 \mu\text{g}/\text{m}^3$, and $114 \pm 42 \mu\text{g}/\text{m}^3$, respectively. There were no indications that divergent emissions originated from different stations. Emission factor values for all parameters were $1.3 \times 10^{-3} \text{ g}/\text{kg}$ (PM_{10}), $0.01 \text{ g}/\text{kg}$ (CO), $1.1 \times 10^{-4} \text{ g}/\text{kg}$ (SO_2), $4 \times 10^{-4} \text{ g}/\text{kg}$ (NO_2), and $6 \times 10^{-5} \text{ g}/\text{kg}$ (O_3). Among the gases produced by peat combustion, CO recorded the highest concentration, due to the high carbon content of the peat soil. The phase of combustion also influenced the emission of particulate matter and gases from peat soil combustion. The composition of particulate matter emitted from peat soil combustion was dominated by NO_3^- and Na^+ . The high content of these ions may well be due to the availability of these particular elements from natural sources, such as sodium from the salt content in sea breeze and nitrogen from the nitrification process in soil. The concentration of heavy metals in PM_{10} peat soil combustion was dominated by Zn. This may be the result of anthropogenic sources, which is further validated by a high enrichment factor value. Analysing the composition of the major anions, cations and heavy metals determined, which were around 20% of the PM_{10} composition, we expected the remaining composition of PM_{10} to be of elemental and organic carbon. The high concentration of levoglucosan indicates that it can be a good indicator for peat soil combustion.

This study shows that emissions from peat combustion may significantly pollute ambient air. As such, the management of peatlands is crucial, as land clearing by biomass burning in peatlands has been shown to cause severe haze episodes in the Southeast Asia region. Consequently, mitigation measures, such as peat fire controls and a zero open burning policy need to be implemented, particularly during the dry season. Future research studies on peat soil combustion need to consider using a proper control chamber that can duplicate the real condition of biomass burning, particularly in Southeast Asia. The information regarding combustion temperature and air and fuel ratio will play a major role in burning peat.

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