# LAPORAN PENELITIAN

## *"Characterization of carbonaceous compounds emitted from Indonesian surface and sub surface peat burning"*

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# Characterization of carbonaceous compounds emitted from Indonesian surface and sub surface peat burning


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ABSTRACT

Indonesia has been experiencing an annually reoccurring forest fire events over the peatlands in eastern Sumatera and western Kalimantan and the impacts on the air pollution episodes in the surrounding countries gained international concerns. The most notable events were in 1997 and 2015 which caused significant losses both on human health and economy in the region. Fires in peat layers could spread radially due to peat structure and emitted substantial amount of aerosols containing carbonaceous compounds, including BC/EC and OC. In this study, peat samples from different levels of depth were collected from western part of Kalimantan and were burned in a combustion chamber received from Kyoto University. Particulate ($PM_{2.5}$) samples from burning experiments were collected and the carbonaceous components (i.e. BC/EC and OC) were also analyzed, respectively. The results showed that average concentration of $PM_{2.5}$ emitted from the combustion of the surface peat (SF) samples was 7,467 ± 3,976 μg/m$^3$, while the corresponding value for the subsurface (SSF) was 5,693 ± 2,137 μg/m$^3$. In average, EC and OC compositions were 1.9% and 70% to the total of $PM_{2.5}$ concentrations, respectively. Emission factors (EFs, in g/kg) were estimated for $PM_{2.5}$, EC, and OC for SF samples of 4.51 ± 0.42, 0.21 ± 0.17, and 3.77 ± 0.82, respectively. The associated EFs for SSF samples were 4.53 ± 1.67, 0.1 ± 0.09, and 1.82 ± 0.43 g/kg, respectively. The results may substantially contribute to fill in the gaps of the availability of EFs for both SF and SFF peat fires in the country to improve the existing PM emission database.

## 1. Introduction

Indonesia has a largest forest reserved area in the world with extensive peatland areas of approximately 20.6 million ha (Wibowo and Suyatno, 1998). Peatland areas are dominantly utilized as an agricultural land in Indonesia and a traditional slash and burn (SAB) method is still commonly practiced for land clearing due to its easiness, economic and effect to enrich soil. This often leads to the annually reoccurring peat fire events which burned of approximately 1.5–2.2 million ha of peatland annually in both Sumatera and Kalimantan Island. Peat fires are known to be more dangerous than the above biomass forest fire events because it can last longer and the fire reaches deeply to the subsurface part of the peatland to make it more difficult to control. Total estimated annual emission of $CO_2$ was reported to be 3,000–9,400 Mega tons and it contributed of 40% of the global $CO_2$ emissions (Hooijer et al., 2006). Massive amounts of toxic air pollutants are emitted to the atmosphere leading to detrimental effects on human health and premature mortality in the affected areas including the neighboring countries (Permadi and Kim Oanh, 2013; Koplitz et al., 2016).

Peat fires emitted large amount of fine particulate emissions including the substantial amount of organic carbon (OC) and black carbon (BC) emissions. Particulate with the aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is known as the most toxic air pollutant that is very harmful to human health and is closely linked with the premature mortality (Betha et al., 2013). Organic carbon is a complex mixture of hundreds organic compounds (Watson et al., 2005; Seinfeld and Pandis, 2006) and it contributes dominantly to the total particulate emission of peat fires. It also contributes to offset the global warming by scattering the incoming solar radiation hence cooling down the surrounding atmosphere. Black carbon, also named as elemental carbon (EC), is known as a product of incomplete combustion which can absorb the

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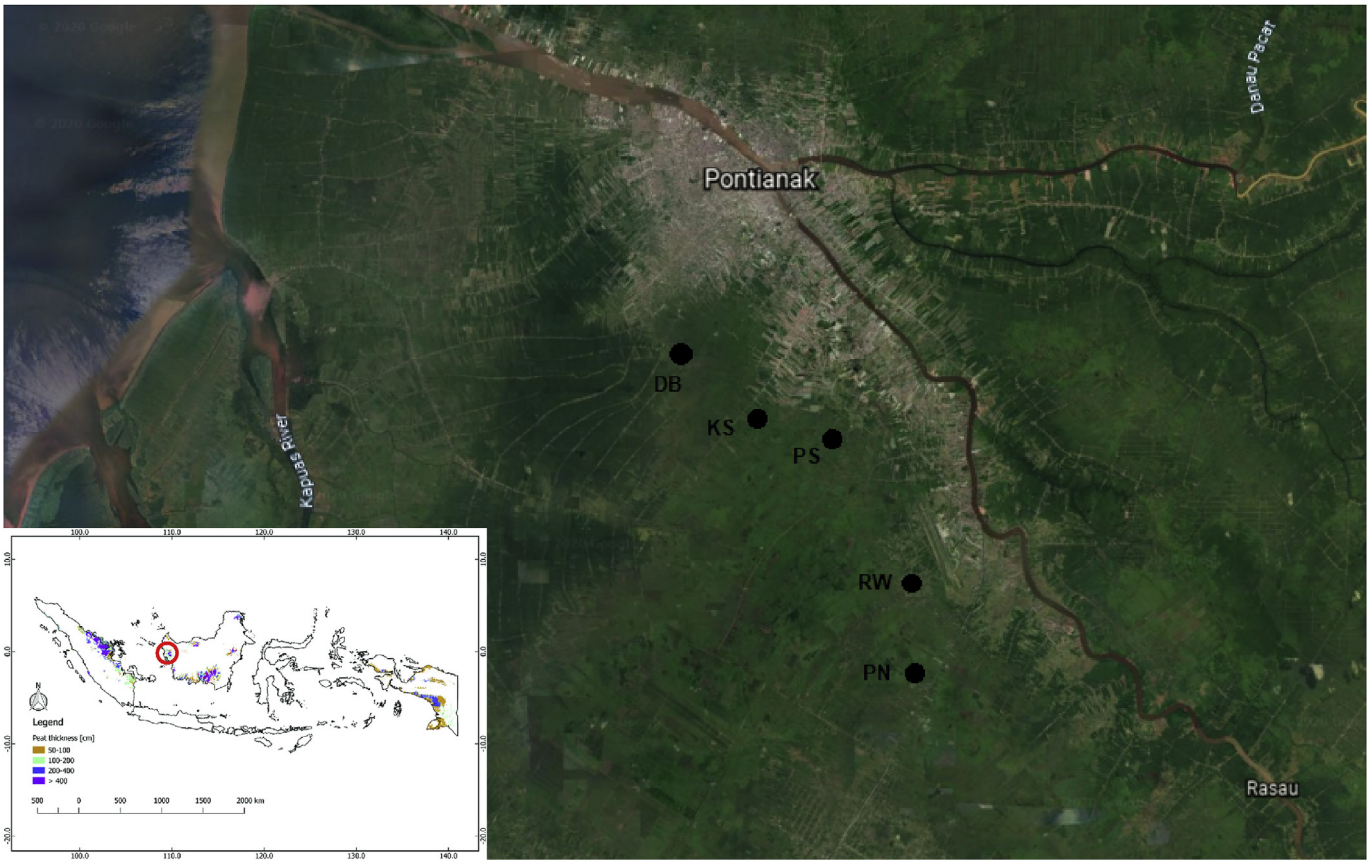


**Fig. 1.** Sampling location. Source of peatland thickness map: Minasny et al. (2019).

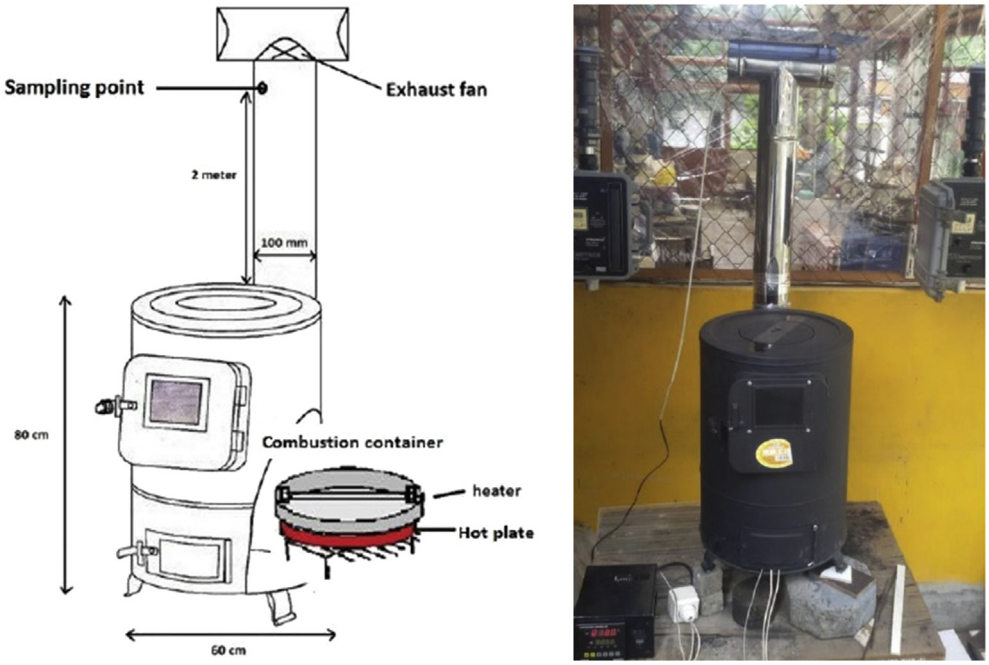


**Fig. 2.** Scheme of the combustion chamber. Adapted from Setyawati et al. (2017).

incoming solar radiation hence it contributes to the global warming (Hansen and Nazarenko, 2000).

Previous estimates of the total forest fire emission of Indonesia have been reported but peat fire emission was not included due to difficulty in estimating the depth of the burning and the absence of locally measured peat fire emission factors (EFs) (Permadi and Kim Oanh, 2013; Shi et al., 2019). Several studies were conducted to measure concentrations of $PM_{2.5}$ and carbonaceous compounds from the Indonesian peat combustion and the results showed extremely high concentrations of $PM_{2.5}$ (Fujii et al., 2014). However, the EFs were not

**Table 1**
Dried peat samples characteristics.

| No. | Sample | Moisture (%) | C-Organic (%) |
|---|---|---|---|
| 1 | PS1 | 12.8 | 55.9 |
| 2 | PS2 | 12.6 | 52.7 |
| 3 | DB1 | 12.2 | 56.3 |
| 4 | DB2 | 11.7 | 48.9 |
| 5 | KS1 | 15.3 | 58.1 |
| 6 | KS2 | 15.0 | 57.9 |
| 7 | PN1 | 11.3 | 44.6 |
| 8 | PN2 | 10.9 | 36.5 |
| 9 | RW1 | 14.2 | 56.8 |
| 10 | RW2 | 13.7 | 54.4 |
| Average (all samples) | | 12.9 ± 1.5 | 52.2 ± 6.9 |
| Average (SF peat)[a] | | 13.2 ± 1.6 | 54.3 ± 5.5 |
| Average (SSF peat)[b] | | 12.8 ± 1.6 | 50.1 ± 8.2 |

Note.
[a] SF samples are denoted with 1.
[b] SSF samples are denoted with 2.

reported as such, except from the long-aged study without detail information on the depth of the peat samples taken. Other laboratory studies focused only on the overview of the $PM_{2.5}$ emission of the surface peat fires without further details on the carbonaceous compound emissions (Othman and Latif, 2013). There is still a need to focus on the subsurface peat emission measurement because in fact peat fires can penetrate deeper from the surface.

This study analyzed the composition of the BC/EC and OC in particulate emissions from the combustion of peat samples taken from the different levels of depth of both surface (SF) and sub surface (SSF). Peat samples characteristics were analyzed including pH, carbon content, moisture content, ash content, and soil organic content. Further, samples were burned in a combustion chamber received from Kyoto University and emissions of $PM_{2.5}$, BC/EC, and OC were measured and the compositions were analyzed. Emission factors of PM and short-lived climate forcing pollutants (SLCPs) such as BC and OC were generated and were compared with the available data. Existing global fire emission inventories assumed that all peat layers were fully burned and single EF was used for emission calculation. Therefore, the results may contribute to provide Indonesian peat burning $PM_{2.5}$, BC/EC, and OC EFs based on SF and SSF (different peat depths) in which to our knowledge has been limitedly available. This will further contribute to develop more accurate peat burning emission inventory results in term of total mass and compositions (source profile).

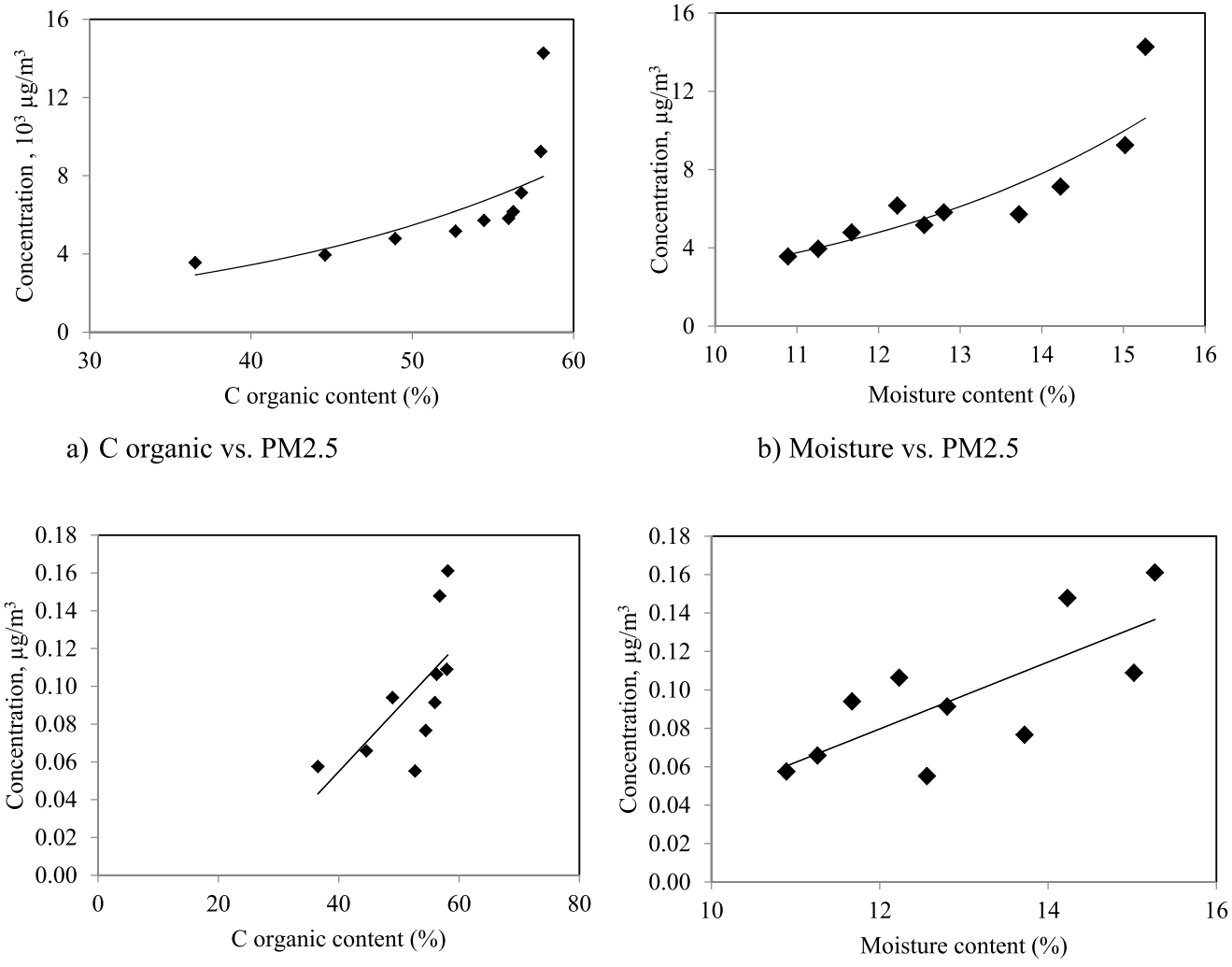


**Fig. 3.** Correlations between carbon organic and moisture contents with the concentrations of $PM_{2.5}$ and BC.

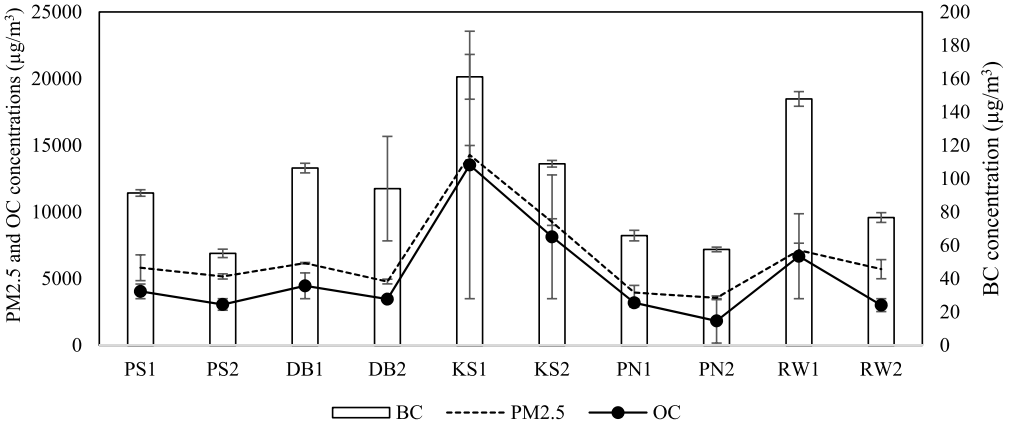


**Fig. 4.** $PM_{2.5}$, OC, and BC concentrations measured in each peat sample burning.

## 2. Methodology

### 2.1. Sample collection and analysis of peat soil characteristics

Peatland areas in Indonesia are mainly scattered at the western coast of Kalimantan (33.9%) especially in Kubu Raya district (Fig. 1). In this district, the area of peatland is 342,983 ha and peat samples were collected from this district. In this area, the peat thickness varies from 100 cm to > 400 cm (Minasny et al., 2019) therefore SF and SSF peats are commonly found. This district is located 52 km to the Southern part of the capital city of West Kalimantan Province, Pontianak City (670,000 inhabitants in 2019). In between, the International Airport of Supadio is located. Large industries found in the capital city are rubber, wood and food processing industries (BPS Kota Pontianak, 2019).

We collected information on number of hotspot and peat depth map (Minasny et al., 2019) and revealed that intensive peat burning occurred in Kubu Raya district. Note that, before peat soil sampling was undertaken, preliminary surveys were done in Kubu Raya district for peat depth data collection and determination of sampling points that can represent a wide variety of level of peat depth. We highlighted several locations where the peat fires occurred few days back then we marked the locations in the map with a help from colleagues from the University of Tanjungpura, Pontianak. We then interviewed local people to exactly reach the places where the peat fires occurred and to get permission from the local authority and land owner. Detailed coordinates of the sampling points are presented in Fig. 1. Peat samples (SF and SSF) were drilled at five (5) sampling points. Five sampling points were selected from the previously collected information on subdistricts which have largest peat areas as well as the peat depth. It was planned that in one location both SF and SSF samples were collected. Peat samples were then coded based on the local name of sampling locations, i. e, Parit Senbin (PS), Disbun (DB), Komplek Srikandi (KS), Pabrik Nanas (PN), and Rasau Jaya (RW). Peat samples that were taken at the SF (0.0–0.5 m) were coded with 1 (PS1, DB1, KS1, PN1, and RW1) while the samples that were taken from the SSF (1–1.5 m) were coded with 2 (eg PS2, DB2, KS2, PN2, and RW2).

Peat sampling was conducted using drilling with a tube sampler with a diameter of 10 cm and the length of 50 cm to obtain the mass of peat, each for 5 kg. Peat samples were then placed in cooler boxes. Further, peat soil characteristics were analyzed including pH, water content, ash content, soil organic matter (SOM), and other organic soil. Sampling apparatus was obtained from the local university of Tanjungpura, West Kalimantan. Peat soil pH value was measured using the method which referred to the Technical Guidelines for Chemical Analysis of Soil, Plant, Water, and Fertilizer (Department of Agriculture, 2005). Water content was determined using the Indonesian national standard method (SNI 13-6793-2002) on moisture testing methods. C-organic content of peat was analyzed using the Walkley Black method as guided in the SNI 13-6793-2002.

### 2.2. Burning experimental set-up and analysis

Before the peat soil was burned, it was initially dried following the method described in Othman and Latif (2013) to represent actual condition in the field. An amount of 500 g of peat sample was weighted and was placed into a container. Samples were burned in a combustion chamber provided by Kyoto University, Japan. The picture of the chamber is presented in Fig. 2. Burning temperature was monitored regularly using a digital thermometer and the maximum value was achieved at ± 300 °C. Burning experiments were conducted for all samples (i.e. SF and SSF samples) collected from the field.

Particulate emission of $PM_{2.5}$ from peat sample burning was collected using 2 unit of Mini Volume Tactical Air Sampler (MiniVol TAS) using both teflon and quartz fiber filters. Teflon filter was used for $PM_{2.5}$ mass and BC using reflectance method while samples collected on the quartz fiber filters were sent to Kyoto University Japan to analyze EC/OC. The maximum flow rate of the MiniVol was set to 5 L per minute (lpm) in order to enable the $PM_{2.5}$ to be collected to the impactor (Lane et al., 2001). Before using, the flow rate of the MiniVol TAS was calibrated using the primary standard of the bubble meter to get an accurate value of 5 lpm (Operation Manual, 2014). Methanol was used to clean important parts of the sampler such as filter holder, preseparator, and impactor. Quartz fiber filters were pre-baked on the temperature of 900 °C for 4 h and were conditioned in the desiccator for 48 h prior to the sampling. Blank filter samples were also collected in petry dishes and were placed in the desiccator for 48 h prior to gravimetric analysis.

For gravimetric analysis, filters were weighted before and after the sampling using a 5 digit balance (brand BOECO Germany) at the air quality laboratory of Environmental Engineering Department of ITB. Three times reading were done for each sample. Temperature and relative humidity in the room were regularly recorded. BC concentrations (from the Teflon filters) were measured using EEL Smoke Stain Reflectometer Model 43D. The device was initially calibrated using previously developed calibration curve by the Asian Institute of Technology to correct the reading of the reflectance values which were then correlated with BC concentrations. Volume of air sampled was calculated from the flow rate and duration of sampling while the concentrations at the standard conditions for $PM_{2.5}$ and BC were calculated using the recorded actual temperature and pressure data.

Other carbon fractions (EC and OC) were analyzed using a Thermal/Optical Carbon Analyzer Model 2001, following the DRI of the

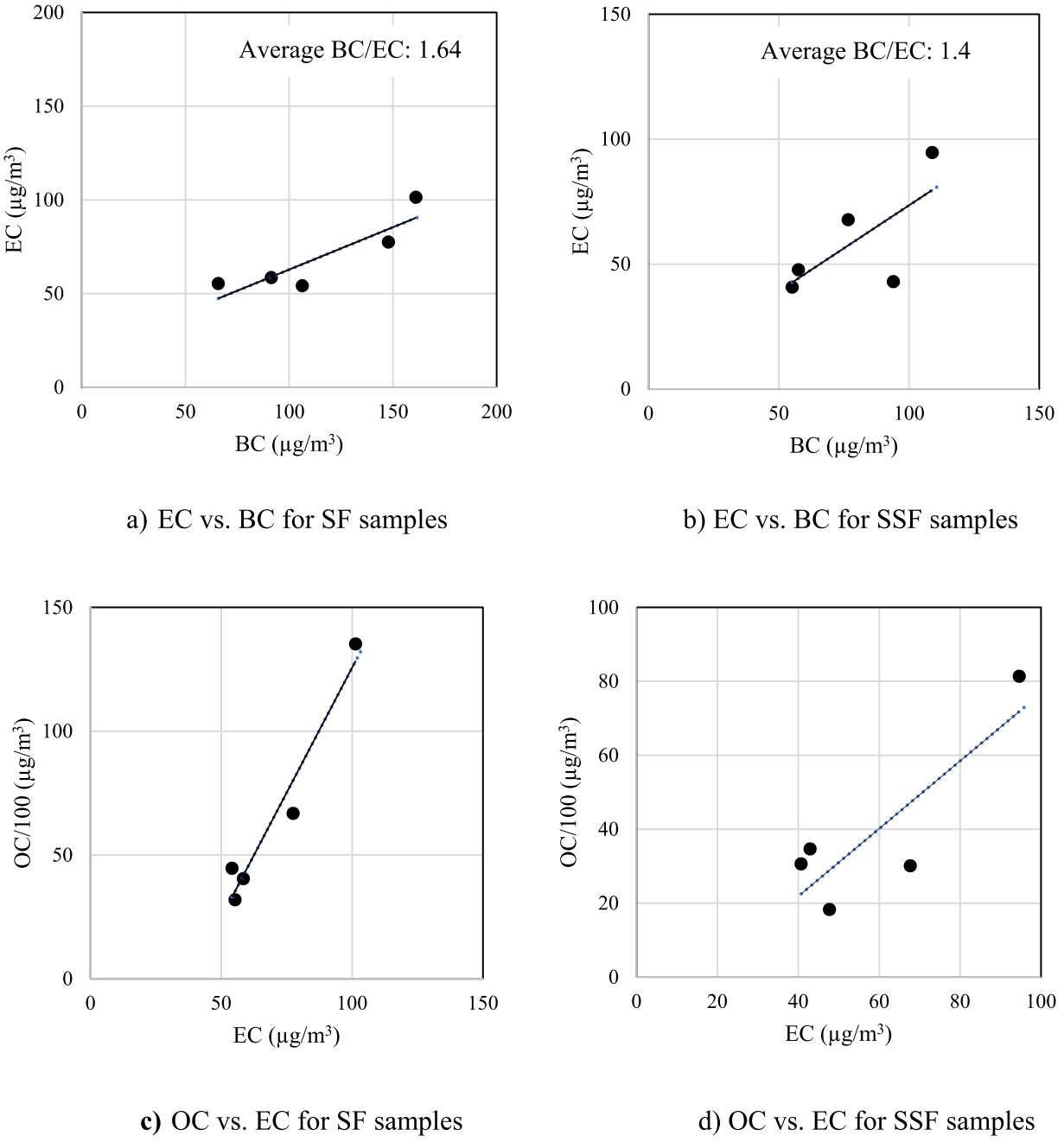


**Fig. 5.** Scatter plots of EC vs. BC and OC vs. EC from SF and SSF sample burning.

IMPROVE-A temperature protocol provided at the laboratory Department of Socio-Environmental Energy Science Graduate School of Energy Science, Kyoto University, Japan. Composition of OC from aerosol in each burning peat sample was characterized using DRI Model 2001 OC/EC Carbon Analyzer. IMPROVE_A defines range of separating temperature for each carbonic fraction by thermal. The process is described as follows (Chow et al., 2007; Fujii et al., 2014): 140 °C for $OC_1$, 280 °C for $OC_2$, 480 °C for $OC_3$, and 580 °C for $OC_4$ with helium (He) as carrier. Meanwhile, temperature for elemental carbonic is as follows: 580 °C for $EC_1$, 740 °C for $EC_2$ and 840 °C for $EC_3$ with carrier gas composed of Helium (He) and Oksigen ($O_2$). Organic carbon, EC and total carbon (TC) were calculated from eight fractions of carbon using the relations described in Fujii et al. (2014). Further fractions of BC, EC/OC to the total mass of $PM_{2.5}$ were calculated and analyzed for both SF and SSF burning experiments.

### 2.3. Emission factor calculation

Prior to burning experiments, the amount of initial peat was weighted and after burning the unburned peat (remaining ash) was also collected and its mass was determined. Thus, the amount of burned peat could be estimated. This procedure was done for each burning experiment for all samples. Further emission factors (g of pollutants per mass of peat burned) at the standard conditions were determined using the following relation:

$$EF = \frac{(C \times V_{std})}{M} \times 10^{-6} \quad (1)$$

EF = emission factor (g/kg)
C = concentrations of $PM_{2.5}$, BC and EC/OC (µg/m³)
$V_{std}$ = volume of air sampled at standard conditions (m³)

**Table 2**
Shares of each carbon fraction to the total TC concentration.

| Sample | Shares (%), TC = OC + EC[a] | | | | | | | | TC (μg/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|
| | OC1 | OC2 | OC3 | OC4 | OP | EC1 | EC2 | EC3 | 4,101 |
| PS1 | 53.33 | 25.03 | 12.02 | 3.53 | 5.06 | 3.27 | 2.66 | 0.16 | 3,104 |
| PS2 | 44.33 | 29.74 | 13.51 | 4.57 | 6.53 | 4.59 | 2.79 | 0.46 | 4,607 |
| DB1 | 54.97 | 29.18 | 6.38 | 1.18 | 7.77 | 6.71 | 1.44 | 0.13 | 3,507 |
| DB2 | 47.07 | 35.95 | 8.83 | 1.78 | 5.56 | 4.48 | 1.71 | 0.17 | 14,010 |
| KS1 | 55.52 | 29.09 | 5.26 | 0.63 | 9.06 | 8.88 | 0.57 | 0.05 | 8,382 |
| KS2 | 52.18 | 35.96 | 6.07 | 0.98 | 4.34 | 3.61 | 1.08 | 0.12 | 3,290 |
| PN1 | 49.64 | 29.40 | 11.82 | 3.49 | 5.10 | 3.72 | 1.82 | 0.10 | 1,905 |
| PN2 | 37.50 | 18.14 | 23.96 | 6.74 | 11.22 | 6.92 | 5.91 | 0.83 | 6,857 |
| RW1 | 48.01 | 32.12 | 12.99 | 0.97 | 5.05 | 4.56 | 1.22 | 0.13 | 3,079 |
| RW2 | 30.83 | 19.00 | 29.52 | 8.54 | 10.27 | 6.22 | 5.61 | 0.28 | 5,284 |
| Average | 47.34 | 28.36 | 13.04 | 3.24 | 7.00 | 5.30 | 2.48 | 0.24 | 3,439 |
| Standard dev. | 7.95 | 6.12 | 7.92 | 2.70 | 2.45 | 1.81 | 1.86 | 0.24 | 4,101 |

EC = EC1 +EC2 +EC 3 - OP.
TC = OC + EC.
Note:
[a] Based on Fujii et al. (2014) OC = OC1 + OC2 + OC3 + OC4 +OP.

M = mass of burned peat (kg)

## 3. Result and discussion

### 3.1. Peat soil characteristics and PM2.5 emissions

Two main parameters were measured for all dried samples before the burning experiments: moisture content and C organic content and the results are presented in Table 1. Overall, the moisture content of all samples has an average value of 12.9% while the C organic content was 52.2%. SF peat has a slightly higher moisture content (13.2%) than the SSF peat of 12.8%. Typical value of the moisture content of both SF and SSF because all samples were treated similarly by drying under the sunlight at the same time. SF peat average value of C organic content (54.3%) was also measured higher than the SSF peat of 50.1% showing that the top-soil was dominated by humus with higher C organic content. Christian et al. (2003) measured C organic content and fuel moisture of Indonesian peat of 54.7% and 30.5%, respectively. Our samples have comparable C organic content while the moisture is lower due to pre-treatment of drying under the sunlight.

The effects of both parameters on PM emissions (PM2.5 and BC) during burning experiments are presented in Fig. 3. There were positive correlations between both carbon organic and moisture contents with the $PM_{2.5}$ and BC concentrations. The effect of fuel moisture on $PM_{2.5}$ emission was clear as it tends to decrease the combustion efficiency by absorbing energy available for combustion hence increase $PM_{2.5}$ emission. Higher moisture tends to shift combustion condition from flaming to smoldering thus increasing the emissions of the product of incomplete combustion (i.e. CO, $PM_{2.5}$ and BC). Depending on combustion efficiency, effect of carbon organic on PM emission was less clear especially to investigate the fraction of carbon in peat which was converted to carbon-containing gaseous and carbonaceous PM. In this study, higher values of carbon organic and moisture contents would result in higher concentrations of $PM_{2.5}$ and BC for both SSF and SF peats burning. Both parameters were more positively correlated with $PM_{2.5}$ rather than BC. Overall, SF peat samples have higher average values of both carbon organic and moisture content of 54.3% and 13.2% as compared to the SSF peat samples (50.1% and 12.8%, respectively). Therefore, the concentrations of $PM_{2.5}$ and BC in the SF peat emissions were also higher than the SSF peat.

### 3.2. Emissions of $PM_{2.5}$, BC and EC/OC

The results of $PM_{2.5}$, BC and OC concentrations emitted from burning experiments are presented in Fig. 4. Overall, the average $PM_{2.5}$ concentration measured during the burning experiments was 6,580 ± 3,151 μg/m$^3$. The highest $PM_{2,5}$ concentration was obtained from the burning experiment of KS1 sample of 14.9 × 10$^3$ μg/Nm$^3$ while the lowest concentration was obtained from burning of PN2 sample of 4 × 10$^3$ μg/Nm$^3$. Burning the SSF sample from the KS location also yielded higher concentration of $PM_{2.5}$ as compared to other samples. In average, it can be seen that $PM_{2,5}$ concentration of the SF peat (7,467 ± 3,976 μg/m$^3$) was higher than the SSF peat (5.693 ± 2.137 μg/m$^3$). Burning peat samples in a closed chamber emitted higher $PM_{2.5}$ concentrations as compared to other biomass fuel for example rice straw of only within a range of 1,000–3,000 μg/m$^3$ (Kim Oanh et al., 2011). Unlike the above ground biomass open burning, peat soil burning was mainly dominated by the smoldering condition especially for the SSF peat thus may emit more PM emissions.

Overall, the average BC concentration that was produced from all peat burning experiments is 96 ± 36 μg/m$^3$. In these experiments, sample KS1 produced the highest BC concentration of 161 ± 27 μg/m$^3$ while the lowest BC concentration was generated when the sample of PS2 was burned. Consistent with $PM_{2.5}$ results, BC concentrations produced by the SF peat burning were generally higher than those generated by SSF samples. The SF peat samples emitted BC with an average value of 114 ± 40 μg/m$^3$ while the SSF peat burning emitted BC with an average value of 78 ± 23 μg/m$^3$. OC highest level was seen for the burning experiment of sample KS1 of 13,500 μg/m$^3$, while the lowest concentration was achieved by the burning of PN2 sample of 1,830 μg/m$^3$. Overall, the average OC concentration of the SF peat burning was 6,380 μg/m$^3$ which was higher than that measured for the SSF peat burning of 3,900 μg/m$^3$.

Black carbon concentrations were then compared with the EC concentrations for SF and SSF samples and the results are presented in Fig. 5. It was obviously seen that there was a discrepancy between BC and EC but somehow there were positive correlation. A significant difference in the concentrations of BC and EC measured by two different techniques was observed with BC mass concentrations were always higher than the EC concentrations. As a way of example, the highest concentrations of BC and EC were similar for KS1 while the lowest were also similar for PS2 sample. BC concentrations were measured higher (average of 96 μg/m$^3$) than the concentrations of EC (average of 64 μg/m$^3$). Average BC and EC ratio for SF samples was 1.64 while for SSF was 1.4 showing that BC and EC values were closer for SSF. We also plotted OC and EC for SF and SSF samples in Fig. 5 and the results showed positive correlations for both. It was clear that when the OC concentrations were high (SF) then the BC and EC values were less closer (average of BC/EC for SF was 1.64). In contrast, when the OC concentrations were measured lower (SSF), then the values of BC and

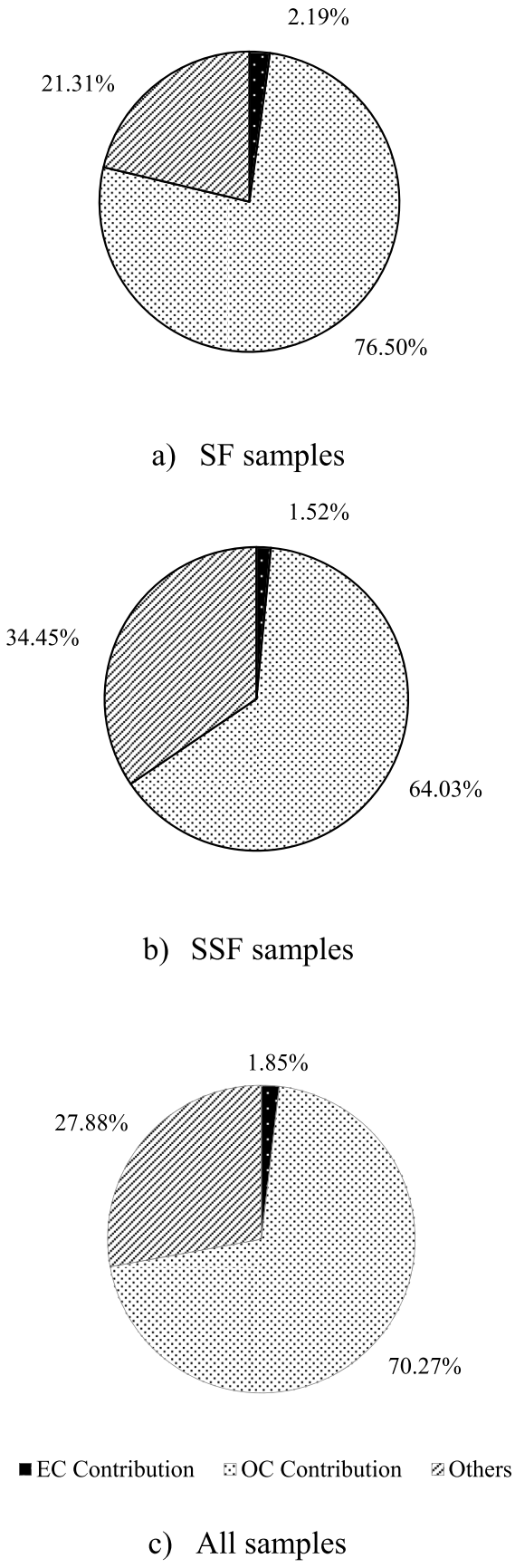


**Fig. 6.** Composition OC, EC and other compounds in total particulate ($PM_{2.5}$) for SF, SSF and all samples.

EC concentrations were closer (average BC/EC of 1.4). Similar conditions were also reported by Singh et al. (2014) who suggested relatively large difference between the BC and EC when the mass concentrations of particulate OC concentrations are relatively high during the crop residue open burning episode. High contribution of light-absorbing organic aerosols during the combustion of peat can also contribute to the difference between BC and EC concentrations.

Shares of each carbon fraction to the total carbon (TC) concentration are presented in Table 2.

It can be seen that all of the peat samples burning were dominated by OC1 as organic carbon that was derived from the burning at temperature of 140 °C with shares of 31–56%. Generally, OC1 was abundant for biomass burning (Chow et al., 2004; Gu et al., 2010). It was followed by OC2 which was reflected as carbon fraction emitted from the coal burning with shares of 18–36% (Chow et al., 2004). This can be understood because peat soil was generated from the degradation of vegetation hence burning this material would release significant amount of OC2.

### 3.3. Contribution of carbonaceous compounds to $PM_{2.5}$

Average shares of carbonaceous compounds to total concentration of $PM_{2.5}$ for SF, SSF and all samples are presented in Fig. 6. When we separated the two samples (Fig. 6a and b), there was a discrepancy in term of carbonaceous compounds share to the total $PM_{2.5}$. SF peat contributed higher OC (76%) compared to SSF of 64% as well as for SF EC (2.19%) as compared to SSF EC of 1.52%. This was because SF had higher amount of organic C content (54%) as compared to the SSF peat of only 51% thus the contribution of OC was higher. For all samples, it was found that OC contributed dominantly (about 70%) followed by other compounds (28%) and EC (2%). In general EC/BC has a large contribution in the fossil fuel combustion (Hansen and Nazarenko, 2000) while OC has a major contribution in the particulate emissions from the combustion of biomass (Gu et al., 2010). OC/EC ratios were found to be 28–75, varied by samples, that were in-line with the previous research conducted by Fujii et al. (2014) who estimated the ratio of OC/EC from peatland fires of 36% from the field burning experiment.

### 3.4. Emission factors of $PM_{2.5}$, EC(BC) and OC

Emission factors of $PM_{2.5}$, EC and OC for both SF and SSF peat burning are presented in Table 3 together with other EFs obtained from other works. We estimated $PM_{2.5}$ EFs nearly similar between SF and SSF (4.51 and 4.53 g/kg, respectively) but EC and OC emission factors of the SF peat burning were higher than the SSF. All EFs were lower than the other reported values for peat, forest fires, or crop residue but our results were closer to those measured by Black et al. (2016). Through laboratory peat burning experiment, Black et al. (2016) calculated EFs of $PM_{2.5}$, BC and OC of 5.9, 0.08, and 4.3, respectively and the values were fairly comparable to our results for SF peat. Therefore, if SSF peat burning was excluded in an emission inventory, total $PM_{2.5}$ emission may not be affected but BC and OC emissions would be likely overestimated.

## 4. Conclusions

All peat soil samples burnt in this laboratory experiment emitted high concentration of $PM_{2.5}$ with the average concentrations of 6,580 ± 3,151 μg/m$^3$. BC concentrations were much lower with the average concentration of 96.49 ± 35.98 μg/m$^3$ while OC and EC accounted for 70.27% and 1.85% of the total mass respectively. $PM_{2.5}$ concentration was higher for SF soil peatland burning sample of 7,467 ± 3,976 μg/m$^3$ than the SSF of 5,693 ± 2,137 μg/m$^3$. BC concentration was also higher for the burning of SF peat than the SSF sample because of higher value of organic carbon material and moisture. Emission factors of SF peat for $PM_{2.5}$, BC, EC and OC were

**Table 3**
Emission factors of $PM_{2.5}$, BC, EC and OC for SF and SSF peat burning (g/kg).

| Parameters | SF | SSF | Other works |
|---|---|---|---|
| EC(BC) | 0.21 ± 0.17 (0.13 ± 0.05) | 0.1 ± 0.09 (0.09 ± 0.03) | 0.66[a]; 0.2[b]; 0.1[c]; 0.94[d], 0.08[f] |
| OC | 3.77 ± 0.82 | 1.82 ± 0.43 | 5.2[a]; 6.2[b]; 14.2[c], 4.3[f] |
| $PM_{2.5}$ | 4.51 ± 0.42 | 4.53 ± 1.67 | 18.9[c]; 7.9[e], 5.9[f] |

Note: average and standard deviation values were derived from 5 sites.
[a] Andreae and Merlet (2001). Above biomass of tropical forest.
[b] Akagi et al. (2011). Values are applicable for SF peat burning.
[c] Andreae (2019). Values are applicable for peat burning.
[d] Hafidawati et al. (2017). Determined from field burning experiment for typical for rice straw in Indonesia.
[e] Hafidawati et al. (2016). Applicable for rice straw open burning in Indonesia.
[f] Black et al. (2016). Laboratory peat burning experiment.

estimated of 4.51 ± 0.42, 0.13 ± 0.05, 0.21 ± 0.17, and 3.77 ± 0.82, respectively while for the SSF were 4.53 ± 1.67, 0.09 ± 0.03, 0.1 ± 0.09, and 1.82 ± 0.43 g/kg, respectively. The results for SF EFs were fairly comparable to the existing study while SSF EFs were calculated lower. This research in particular contributes to the improvement of the PM emission inventory by providing locally measured EFs for PM and carbonaceous compounds of peatland burning in Indonesia for both SF and SSF peats. Particulate emission estimation for underground peat burning in Indonesia should use the SSF EFs to produce more accurate emission database.

## CRediT authorship contribution statement

**Puji Lestari:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Fathi Muthmainnah:** Data curation, Writing - original draft. **Didin Agustian Permadi:** Writing - original draft, Writing - review & editing, Visualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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