A study of the volatile organic compound emissions at the stacks of laboratory fume hoods in a university campus

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A B S T R A C T

Volatile organic compounds (VOCs) are potentially harmful air pollutants that are commonly encountered in urban environments. Various chemicals known to produce VOCs are used in laboratory fume hoods; however little research has been done to show the effect of such chemicals and associated VOCs on the local air quality. This study aims to assess the concentration of various VOCs emitted from the exhaust stacks of rooftop fume hoods mounted on laboratory buildings, as well as to determine factors that contribute to different concentrations of commonly encountered VOCs.

A total of six university campus buildings, comprising four laboratory buildings and two non-laboratory buildings as controls, were selected as case studies. VOCs were sampled using activated charcoal tubes in front of fume hood exhausts located on the rooftops of buildings and were analyzed GC/FID. Factors such as meteorological conditions and the amount of chemicals utilized in the building of interest were investigated.

A total of 11 individual compounds were quantified in the samples collected. The concentrations of 11 VOCs at laboratory buildings were significantly higher (GM; 184.74 mg/m³, GSD; 3.38) than those of non-laboratory buildings (GM; 12.1 mg/m³, GSD; 1.64, p < 0.001). The concentrations of 10 individual compounds emitted from laboratory buildings were significantly higher than those emitted from non-laboratory buildings (p < 0.001) with the exception of m- and p-xylene (p = 0.155). We found that the amount of chemical use was the predominant factor determining the composition and concentrations of VOCs found (p < 0.001). From this study, we suggest that installation of an air purification system in fume hood ventilation systems is necessary to prevent atmospheric pollution and adverse health effects in university populations, as well as supporting efforts towards creating ‘green campus’ environments.

1. Introduction

A university campus hosts a variety of activities such as education, research, and other operational tasks. Because of its large area and corresponding consumption of energy and materials, a university campus may be considered a small community that interacts in various ways with the surrounding community (Alshuwaikhat and Abubakar, 2008). The university campus can affect its surroundings in various ways, including by causing environmental problems that may affect the environmental well-being of the surrounding community. Campus sustainability has recently become an important issue at many universities around the world. Many institutions have recognized that the campus can act as an optimal environment for fostering and promoting “green-campus” and sustainable concepts to the general public. This has led to the adoption of various environmental management systems, such as ISO 14001, to remediate environmental degradation (MacDonald, 2005).
On-campus chemical use is one of the most hazardous, and thus challenging, factors affecting university environment management programs. Many laboratory activities, including research and teaching, necessitate the daily use of various chemicals. In laboratories, most chemicals are handled in fume hoods installed as a part of the local exhaust ventilation (LEV) system to protect the researchers’ health and to prevent the deterioration of indoor air quality. Air containing hazardous chemical vapors is vacuumed from laboratories by these systems and vented into the atmosphere through rooftop exhaust stacks. There are 25,692 science and engineering laboratories in universities around Korea (MEST, 2010); however, there is currently no obligation to install air purifiers in laboratory LEV systems to filter out toxic substances from air vented from lab fume hoods.

Currently, three pieces of legislation affect the venting of lab fume hoods in Korea: the Clean Air Conservation Act, the Law on the Creation of Laboratory Safety and Environment, and Safety Guidelines for School Laboratories. According to the Clean Air Conservation Act, purification facilities are mandatory depending on the types of pollutants and emission levels present. However, hazardous emissions from campus research laboratories are not regulated under this law as the scale of chemical use is relatively small compared to industrial facilities. The Law on the Creation of Laboratory Safety and Environment and the Safety Guidelines for School laboratories have recently been enacted owing to concerns regarding the risks posed by the research field; both laws focus on the prevention of accidents and protecting laboratory researchers from adverse health effects rather than environmental effects (Byun and Park, 2010).

Most science and engineering laboratories utilize various types and amounts of chemicals, including organic materials, as well as acidic and basic materials. Among them, volatile organic compounds (VOCs) generated from using organic solvents are of particular concern owing to their known detrimental effects at certain doses; these include carcinogens such as benzene and 1,3-butadiene (Ashford and Miller, 1998). VOCs in the atmosphere can react with ultraviolet rays and contribute to tropospheric photochemical ozone formation over wide areas because of their slow rate of oxidation. They can also indirectly influence the depletion of stratospheric ozone and contribute to global warming (Dewulf and Van Langenhove, 1999). VOCs are emitted in large quantities from anthropogenic sources such as mobile sources, landfills, and industrial complexes located in urban areas. Chemicals used in laboratories are one source of VOCs, but are rarely studied on the campus scale. Fume hoods used in laboratories may be a potential pollution source that exacerbates outdoor air quality degradation stemming from insufficient or non-existent emission controls. Although the volume of emissions from an individual stack is small, it is expected that the sum of contaminants from all stacks within a campus could be significant.

This study examines the concentration of various VOCs emitted from exhaust stacks on the rooftops of several laboratory buildings located on a university campus and assess factors that affect such concentrations. Background VOC concentrations at non-laboratory buildings were simultaneously studied for comparison with the VOC concentrations at the laboratory buildings.

2. Materials and methods

2.1. Subject selection

This study took place on a university campus, located very close to Kwanak Mountain without any particular factory or pollutant sources nearby, in Seoul, South Korea that contains some 1300 science and engineering laboratories. Among the many educational and research buildings on this campus, four laboratory buildings and two non-laboratory buildings as controls were selected. Numerous research laboratories are housed within the four laboratory buildings chosen. These laboratories employ various hazardous chemicals, whereas the two non-laboratory buildings housed no research laboratories.

In the laboratory buildings, exhaust stacks connected to the fume hoods of each individual laboratory were present on the rooftop of each building. Hazardous gases formed by the use of chemicals in each individual laboratory fume hood are vented through these stacks into the atmosphere. Other anthropogenic sources that could affect VOC concentration were not located near the sampling sites.

Table 1 summarizes general information about the selected buildings. In total, 367 stacks were installed among the 164 laboratories in the four laboratory buildings; the average number of stacks per laboratory varied (Mean ± S.D., 2.3 ± 1.8). In building A, many fume hoods are connected to exhaust stacks such that the number of exhaust stacks is smaller (18) than the number of laboratories in the building (26). The size of rooftop is 810 m², but it covered more sampling percent as 73% of total laboratories than building B (1222 m², 42%), building C (1375 m², 11%), building D (1265 m², 30%). In building C and D, the sampling percent that could be covered of total laboratories was lower relatively due to larger sampling area and a number of laboratories. The mean and standard deviation of flow rates per emission stack were 12.6 and 3.6 m³/min-stack.

Organic solvents used at the laboratories within the study were surveyed by questionnaire. As it was difficult to investigate all of the chemicals used in each laboratory, focus was placed on organic solvents which are commonly used in research labs and are ready sources of VOCs. Ethanol, acetone, methylene chloride, n-hexane, chloroform, benzene, toluene, ethylbenzene, xylene (classified into o-xylene and m- and p-xylene), and 1,4-dichlorobenzene use were surveyed.

Table 2 summarizes the type and amount of organic solvent used in each laboratory building. The largest building-scale use of organic solvent was in the pharmaceutical building (building A, 3077 L/month), followed by the agriculture and life science building (building B, 1500 L/month), the engineering building (building B, 1429 L/month), and the natural science building (building C, 667 L/month). In the case of the pharmaceutical building, many laboratory fume hoods were connected to one exhaust stack and a large volume of organic solvents was also consumed inside labs located in the building.

2.2. Sampling and analysis

VOCs were collected from rooftop exhaust stacks twice per sampling area over a period of approximately 8 h (8:30–12:30 and 13:00–17:00) in charcoal tubes (CSC 226-01, SKC Inc., USA) using low-volume pumps (LFS-113, Gilian Inc., USA) with a calibrated constant flow rate of about 0.2 L/min based on NIOSH method 1501 (NIOSH, 1994). As there were many exhaust stacks on the rooftop of the laboratory buildings, we divided the rooftop into four districts according to the location of the stacks and the size of the rooftop area. The sampling points at each district were sufficiently remote not affecting each other and the samples were collected randomly at one spot per district.

All samples, including field blank samples, were stored in a freezer at −20 °C before analysis. Analysis was conducted within 30 days of sample collection. Each sample was extracted using 1 ml of carbon disulfide and analyzed by gas chromatography (GC, HP-6890N, Agilent Technologies, USA) with a flame ionization detector (FID) utilizing the GC Chemstation software program (Rev. A.
### Table 1

<table>
<thead>
<tr>
<th>Building code (college)</th>
<th>Type</th>
<th>Laboratory / Non-laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (College of Pharmacy)</td>
<td>A (Library)</td>
<td>1222 (33.4%) 97 (16.2%) 28.88 16 (2) 28.93 ± 2.12 55.99 ± 5.30 1.09 ± 0.74 1.10 ± 0.60 1.09 ± 0.74</td>
</tr>
<tr>
<td>B (College of Engineering)</td>
<td>A (Library)</td>
<td>1175 (64.1%) 63 (16.2%) 28.88 16 (2) 27.66 ± 2.55 73.81 ± 110 1.95 ± 0.81 1.20 ± 0.61 1.21 ± 1.02</td>
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<td>C (College of Natural Science)</td>
<td>A (Library)</td>
<td>1265 (41.3%) 189 36.59 16 (2) 30.74 ± 3.30 50.80 ± 16.14 1.21 ± 1.02 1.19 ± 0.66 0.54 ± 0.22</td>
</tr>
<tr>
<td>D (College of Agriculture and Life Science)</td>
<td>A (Library)</td>
<td>2065 (31.9%) 63 (11.2%) 11.69 16 (2) 27.66 ± 2.55 73.81 ± 110 1.95 ± 0.81 1.20 ± 0.61 1.21 ± 1.02</td>
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<tr>
<td>E (Dormitory)</td>
<td>B (Library)</td>
<td>1489 (98.8%) 6 (2) 28.22 ± 2.70 68.45 ± 6.91 70.33 ± 4.87</td>
</tr>
</tbody>
</table>

*Note: All values are in parts per million (ppm) unless otherwise specified.*

<table>
<thead>
<tr>
<th>Flows rate (m³/sec)</th>
<th>Total number of laboratories (sampling %)</th>
<th>Volumes of samples collected (ml)</th>
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</thead>
<tbody>
<tr>
<td>0.98</td>
<td>10.0</td>
<td>12</td>
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</tbody>
</table>

#### Table 1 Notes:
- **Building code (college):** A (College of Pharmacy), B (College of Engineering), C (College of Natural Science), D (College of Agriculture and Life Science), E (Dormitory).
- **Type:** A (Library), B (Library).
- **Laboratory / Non-laboratory:** A (Library), B (Library).
- **Flows rate (m³/sec):** 0.98.
- **Total number of laboratories (sampling %):** 10.0.
- **Volumes of samples collected (ml):** 12.

#### Table 2

<table>
<thead>
<tr>
<th>Type</th>
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<th>Number of samples collected</th>
<th>Type of chemicals</th>
</tr>
</thead>
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<tr>
<td>A (Library)</td>
<td>A (College of Pharmacy)</td>
<td>10</td>
<td>Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others</td>
</tr>
<tr>
<td>B (Library)</td>
<td>B (College of Engineering)</td>
<td>8</td>
<td>Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others</td>
</tr>
<tr>
<td>C (Library)</td>
<td>C (College of Natural Science)</td>
<td>12</td>
<td>Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others</td>
</tr>
<tr>
<td>D (Library)</td>
<td>D (College of Agriculture and Life Science)</td>
<td>10</td>
<td>Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others</td>
</tr>
<tr>
<td>E (Library)</td>
<td>E (Dormitory)</td>
<td>6</td>
<td>Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others</td>
</tr>
</tbody>
</table>

*Note: All values are in parts per million (ppm) unless otherwise specified.*

**Table 2 Notes:**
- **Type:** A (Library), B (Library), C (Library), D (Library), E (Library).
- **Building code (college):** A (College of Pharmacy), B (College of Engineering), C (College of Natural Science), D (College of Agriculture and Life Science), E (Dormitory).
- **Number of samples collected:** 10, 8, 12, 10, 6.
- **Type of chemicals:** Acetone, acetonitrile, ethanol, chloroform, toluene, xylenes and others.
Stepwise multiple regression models were used to analyze the differences in VOC concentrations among study buildings and sampling sites at each laboratory building. Following this, significant results determined per the ANOVA test were analyzed using a post hoc Tukey test. Stepwise multiple regression models were used to find the relationships between use of chemicals, flow rate at the fume hood stacks, and meteorological factors including temperature, relative humidity, wind speed, and intensity of UV associated with the VOC concentrations. SAS 9.2 (SAS Institute, USA) was used for statistical analysis of all data acquired in this study.

### 3. Results

#### 3.1. Differences in VOC concentrations outside laboratory and non-laboratory buildings

The four lab buildings investigated housed a total of 164 laboratories, with no laboratory present in either of the two non-laboratory buildings. Anthropogenic indoor sources stemming from the use of chemicals were abundant outside the laboratory buildings. Table 3 and Fig. 1 show the differences in VOC concentrations between the laboratory building group (buildings A, B, C, and D) and the non-laboratory building group (buildings E and F). In Fig. 1 aromatic VOCs, except for benzene, are shown collectively as TEX (the sum of toluene, ethylbenzene, and o-, m-, and p-xylene). The concentrations of eight compounds (those other than ethanol, acetone, and 1, 4-dichlorobenzene) are considered to be hazardous air pollutants (HAPs) by the U.S. Clean Air Act. Ten compounds, with the exception of acetone, are regulated by the Korean Clean Air Act. Ten compounds, with the exception of acetone, are considered to be hazardous air pollutants (HAPs) by the U.S. Clean Air Act.

#### 3.2. VOC concentrations outside each building

Table 4 shows the concentrations of the 11 individual VOC compounds collected at the exhaust stacks of each building. Of the analyzed compounds, the concentrations of eight compounds (other than ethanol, acetone, and 1, 4-dichlorobenzene) are regulated by the Korean Clean Air Act. Ten compounds, with the exception of acetone, are considered to be hazardous air pollutants (HAPs) by the U.S. Clean Air Act.
The concentrations of all compounds except for m- and p-xylene \((p = 0.1326)\) (all, \(p\) values < 0.0001; o-xylene; \(p = 0.0019\)) were significantly different at each building. After post hoc Tukey tests, there were significant differences in the sum of VOC concentrations between laboratory buildings (A, B, C and D) and non-laboratory buildings (E and F). There were no significant differences or significant among individual laboratory buildings in VOC concentrations (Table 5). Among the laboratory buildings, building A has significantly higher levels of acetone \((30.27 \mu g/m^3)\), methylene chloride \((15.00 \mu g/m^3)\), n-hexane \((59.07 \mu g/m^3)\), chloroform \((162.39 \mu g/m^3)\), and BTEX compounds \((42.90 \mu g/m^3)\), not shown in Table 4\) than other laboratory buildings and non-laboratory buildings \((p < 0.001)\). Concentrations measured at building D were the second highest among the three laboratory buildings.

Table 6 shows the correlation between individual VOC components according to Pearson correlation analysis. All compounds except for xylenes and 1, 4-dichlorobenzene were strongly correlated to one another \((p < 0.01)\). Significant correlations were found among acetone, methylene chloride, and n-hexane, which were the most frequently used as solvents or intermediates in laboratories as compared to other chemicals. Aromatic compounds including benzene, toluene, ethylbenzene, and xylenes were mostly associated with each other \((p < 0.01)\), whereas m- and p-xylene demonstrated a relatively weak association \((p < 0.05)\).

### 3.3. Factors associated with VOC concentrations

Table 6 shows the effects of associated factors on VOC concentrations as realized using stepwise multiple regression analysis. To develop this model, the volume of chemicals used and outdoor meteorological factors were considered as independent variables for individual VOC concentrations. Generally, ethanol, acetone, methylene chloride, n-hexane, and chloroform were used in almost all of the laboratory buildings. The use of other compounds varied

![Fig. 1.](image-url) Concentration distribution of individual compounds between (A) laboratory buildings and (B) non-laboratory buildings.
in each building; thus, only the five main compounds were considered. Several of the factors demonstrate strong interrelations, including outdoor temperature and wind speed and the volume of chemical used and number of laboratories in a building; thus, the number of laboratories and wind speed were excluded from the regression analysis.

Table 7 demonstrates significant models derived from multiple regression analysis. The models show that acetone, methylene chloride, n-hexane, and chloroform were significant, but other compounds were not.

The volume of chemicals used was associated with the concentrations of acetone ($\beta = 0.650$, $p < 0.001$), methylene chloride ($\beta = 0.216$, $p < 0.001$), n-hexane ($\beta = 0.468$, $p < 0.001$), and chloroform ($\beta = 1.445$, $p < 0.001$). The number of labs connected to the stacks and relative humidity among the outdoor meteorological factors were associated with the concentration and presence of some VOCs. The number of labs was associated with the concentration of acetone ($\beta = -10.6022$, $p = 0.0004$) and relative humidity was associated with n-hexane ($\beta = 1.8985$, $p = 0.0216$).

Fig. 2 shows the relationship between the sum of 11 VOCs and the total volume of chemical used. Because frequently used chemicals contain large proportions of these 11 VOCs, the sum of these compounds and the total use of chemicals showed a significantly high correlation ($R^2 = 0.49$, $p < 0.001$).

Fig. 3 outlines the relationship between the concentration of individual compounds and the amount of chemicals used. As expected, the volume of chemical used was significantly associated with the concentration of the VOC measured outside the building, except for ethanol. Acetone ($R^2 = 0.59$, $p < 0.001$), methylene chloride ($R^2 = 0.61$, $p < 0.001$), n-hexane ($R^2 = 0.58$, $p < 0.001$), and chloroform ($R^2 = 0.67$, $p < 0.001$) showed a positive correlation with the volume of chemicals used within the building under investigation.

### 4. Discussion

In this study, the presence and concentration of VOC emissions from the exhaust stacks connected to laboratory fume hoods on a university campus were measured. We found that the sum of VOCs detected and the concentrations of individual VOCs were significantly higher at buildings housing laboratories than in the background concentrations measured at non-laboratory buildings.

VOC samples were collected using activated charcoal tubes and pumps. Active sampling has a greater flexibility when measuring low or high concentrations, and activated charcoal can adsorb a wide range of compounds because of its complex surface structure. Therefore, the method has an advantage over passive sampling methods, which involve a lower sampling rate and a high sampling cost (Nothstein et al., 2000; Matisová and Skrabáková, 1995; Wang and Austin, 2006). As the VOC concentrations were expected to be variable, we selected an active sampling method that is used commonly in the field of industrial hygiene. In rare cases, it could be used for sampling VOCs in ambient air in previous studies. Singh et al. (2012) and Do et al. (2013) used charcoal to monitor VOCs in urban atmosphere and Ramirez et al. (2012) used charcoal and Tenax to estimate the chronic risk from exposure to VOCs in the atmosphere near industrial site. Ramirez et al. (2010) also conducted comparative study of solvent extraction and thermal desorption (Tenax) methods for determining VOCs in ambient air.

The combined concentration of 11 VOC species measured outside laboratory buildings was between 84.99 and 393.02 µg/m$^3$, whereas that measured outside the two non-laboratory buildings was between 9.30 and 18.92 µg/m$^3$. There are many potential anthropogenic sources in buildings in general such as detergents, personal-use products, office supplies, and building materials. The VOCs emitted from these products might be important in indoor air quality but trivial in affecting outdoor air quality. As shown in Table 3 and Fig. 1, individual concentrations of 11 VOCs were significantly higher outside the buildings housing laboratories than outside non-laboratory buildings. In particular, the concentration ratios of individual compounds between the laboratory and non-laboratory building groups were significantly different. For instance, the concentration of n-hexane outside the laboratory buildings was 172.75 times that found outside non-laboratory buildings, exhibiting the greatest difference among the individual compounds. The ratio of benzene concentrations between laboratory and non-laboratory buildings was 6.86. High emissions from laboratory buildings could possibly contaminate the air near the building and flow into the building. Of specific note is benzene, which is known to induce toxicity in blood-forming systems and is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) (Glass et al., 2003; IARC, 1987). Because of this, benzene was added to the Air Quality Standard List of Korea in 2006.

This study also showed that VOC concentrations among the laboratory buildings (Table 4) and even among the sampling sites in a building (data not shown) were different. The experiments being conducted in each laboratory are very complex, utilizing a wide variety of chemicals. Because chemicals are also used irregularly depending on experimental schedules, the daily VOC concentrations could fluctuate. Hence, we investigated a monthly volume of the chemicals utilized, which is difficult to correlate to VOC concentrations.

Ethanol, acetone, methylene chloride, n-hexane, and chloroform were frequently used chemicals in the laboratory buildings. The concentrations of these four compounds (excluding ethanol) were strongly associated with the volume of chemicals used. In previous studies, VOC concentrations increased with temperature and wind speed (Cetin et al., 2003; Nguyen et al., 2009), but these outdoor factors did not affect the VOC concentrations in this study. Especially in case of air velocity, the air generated by the exhaust fans was high ($> 8$ m/s), the outdoor wind speed might not affect the VOC concentrations.

A limitation of this study was a lack of accurate information about the chemicals being used in each laboratory and the laboratory conditions. Frequently used chemicals in each laboratory were investigated based on the monthly use, but we were not able to find out exact amounts of chemicals used during sampling and how they were used. Some compounds such as benzene, toluene, and 1, 4-dichlorobenzene showed high concentrations even though our surveys indicated that they were not used much in certain buildings. If information about experimental conditions, physicochemical properties of the chemicals (e.g., vapor pressure), and by-products caused by chemical reactions could be obtained, the source of target VOC compounds could be identified more accurately. Also, we could not accurately match chemicals used in each fume hood with VOCs measured at the rooftops because of the

<table>
<thead>
<tr>
<th>Building</th>
<th>Mean difference of total sum of VOCs</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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<tr>
<td>A</td>
<td>-0.4257*</td>
<td>-0.0204</td>
<td>0.4753*</td>
<td>1.1277*</td>
<td>1.4361*</td>
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<td>0.2024</td>
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<td>1.1481*</td>
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<td>-0.4958*</td>
<td>-0.0204</td>
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<td>D</td>
<td>-0.0462</td>
<td>0.2024</td>
<td>0.4958*</td>
<td>1.1481*</td>
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<td>E</td>
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<td>1.1277*</td>
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<td>0.4753*</td>
<td>1.1481*</td>
<td>1.4566*</td>
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</table>
number of fume hoods and the irregularity of experiment schedules. Furthermore, accurate layouts of building duct systems were unavailable because of remodeling, expansion of the hood system, and poor record keeping.

The concentrations of light hydrocarbons measured within this study may be underestimated because of the sampling media utilized. A large amount of ethanol was commonly used in most laboratories, but its measured concentration was lower than that of heavier compounds (e.g., hexane, benzene). This can be explained by the characteristics of the sampling media. Charcoal derived from coconut shells is not efficient at adsorbing volatile, low-molecular-weight hydrocarbons (Tang et al., 1996). Thus, ethanol could not be efficiently collected with the charcoal tubes utilized in this study because of its low molecular weight and low breakthrough volume. These light compounds are known as simple asphyxiants and correction of environmental standards violations within a university (US EPA, 2000). Savely et al. (2007) introduced the EMS systems which have been proposed specifically for colleges and universities such as the Osnabruck model and ISO 14001. Bero et al. (2012) described challenges and lessons in the design and development in EMS in a real university setting. Among the essential elements of an EMS by ISO 14001 in the paper, we think the element ‘monitoring and measuring operations that could have an environmental impact’ could support the need for our study. Our study could be useful for providing actions to implement periodically above element.

Komnitas and Modis showed a risk map to identify potential hot spots by using geostatistics at the wide coal mining and waste disposal site (Komnitas and Modis, 2009). Our study is a basic research for identifying the levels of air contaminants just emitted from exhaust stacks of some laboratory buildings, not considering other sources such as traffic vehicles on the inner circulation road of campus. It is important to make a risk map to check the air quality in the campus for green campus. Based on this study, it is possible to perform the research about the distribution of air contaminants in the campus using geostatistics. It also should be considered other sources to the risk map of the total campus area and further studies will be needed. Methodology mentioned by Komnitas and Modis (2009) could be used to make the risk map of the campus in the future.

Even though air purification systems are taken for granted within campus in developed countries, more investigation and research is necessary to chart their efficacy in promoting good environmental outcomes. The laboratory fume hood is a way to protect researchers and prevent the contamination of indoor air if properly operated. However, in Korea air purifiers have not been installed in most laboratory ventilation systems, except for laboratories handling radioactive isotopes. Installation of air purifiers should be obligatory to help promote the idea of green and healthy campuses.

### Table 6

<table>
<thead>
<tr>
<th>VOCs&lt;sup&gt;a&lt;/sup&gt;</th>
<th>1</th>
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<sup>a</sup> 1: ethanol, 2: acetone, 3: methylene chloride, 4: n-hexane, 5: chloroform, 6: benzene, 7: toluene, 8: ethylbenzene, 9: m- and p-xylene, 10: o-xylene, 11: 1, 4-dichlorobenzene.

<sup>b</sup> Variables other than the above four VOCs were not significant.
5. Conclusions

VOC concentrations at the rooftop of laboratory buildings at a university campus were characterized. The samples were collected from four laboratory buildings and two non-laboratory buildings, and 11 VOCs were identified from sorbent tubes at the study buildings.

The VOC concentrations of laboratory buildings were significantly higher than background concentrations outside non-laboratory buildings due to the large amounts of chemicals used and the absence of purification systems in the exhaust systems.

VOC concentrations at each laboratory building site differed from one another because of the unique experimental conditions of the laboratories within each building. The amount of chemical used was a critical factor in determining the VOC concentration at the rooftop. Some compounds, including methylene chloride, n-hexane, and chloroform, were affected by temperature and relative humidity. Other factors, such as the intensity of UV, wind speed, and flow rate, at the stack did not affect the measured concentration.

It is necessary to install air purification systems in the fume exhaust systems of university laboratories to prevent outdoor air pollution, as well as to establish environmental best practices as desired in many current university cultures. Based on this study, it is also possible to perform the research about the distribution of air contaminants by showing risk map in the campus using geostatistics. Further studies will be needed to estimate the risk considering other pollution sources of total campus area.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2013.11.024.

References


