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INDOOR AIR POLLUTION: VOLATILE ORGANIC COMPOUNDS IN NON-INDUSTRIAL MICROENVIRONMENTS IN THAILAND

มลพิษอากาศในอาคาร: สารอินทรีย์ระเหยในสิ่งแวดล้อมขนาดเล็กที่ไม่ใช่อุตสาหกรรมในประเทศไทย

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Abstract

This paper was intended to review literature related to indoor air quality research conducted in Thailand during the past decade. The content was devoted to a certain indoor pollutant group which were volatile organic compounds (VOCs). VOCs were present indoors to a wide range of concentrations with a variety of chemical species. This paper discussed the VOC investigations designated to non-industrial microenvironments, which included workplaces, residences, and mass transit. Typically, levels of VOCs found in the non-industrial microenvironments were significantly less than those found in industries. Although concentrations of VOCs in the non-industrial microenvironments may not be high enough to ause an acute health effect, the concentrations even at or below odor thresholds could result in "sick building syndromes (SBS)" with health symptoms including headaches, mucous membrane irritation, dizziness, etc. Furthermore, this paper was extended to discuss VOC mitigation methods, including source control, ventilation, and air cleaning. Each method was briefly described for their theoretical aspects, application examples, and their implementation considerations.

Keywords: indoor air quality, volatile organic compounds, occupant exposure, source control, ventilation, air cleaning

บทคัดย่อ

บทความนี้มีวัตถุประสงค์เพื่อทบทวนและนำเสนองานวิจัยด้านคุณภาพอากาศในอาคารที่มีการศึกษาภายในรอบทศวรรษที่ผ่านมาของประเทศไทย โดยเนื้อหาที่สำคัญของบทความเป็นการอภิปรายจำเพาะเรื่องมลพิษอากาศในอาคารประเภทสารอินทรีย์ระเหย ซึ่งมักตรวจพบในอากาศด้วยความเข้มข้นแตกต่างกันค่อนข้างมากและประกอบด้วยสารเคมีหลากหลายชนิด การอภิปรายจะเน้นทบทวนงานวิจัยที่เกี่ยวข้องเฉพาะการศึกษาในสิ่งแวดล้อมขนาดเล็กที่ไม่เกี่ยวข้องกับอุตสาหกรรม ซึ่งประกอบไปด้วย สถานที่ทำงาน ที่อยู่อาศัย และยานพาหนะขนส่งมวลชน โดยปกติสารอินทรีย์ระเหยในสถานที่เหล่านี้มักตรวจพบในระดับที่ต่ำกว่าที่พบในสิ่งแวดล้อมอุตสาหกรรมอย่างมาก แม้ว่าระดับมลพิษ

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ดังกล่าวอาจไม่สูงถึงระดับที่ก่อให้เกิดผลกระทบต่อร่างกายแบบเฉียบพลัน แต่การได้รับสารอินทรีย์ระเหยในระดับต่ำหรือต่ำกว่าขีดเปลี่ยนการได้กลิ่นของมนุษย์ยังอาจสามารถส่งผลให้เกิด “กลุ่มอาการป่วยเหตุอาคาร” ซึ่งประกอบด้วยอาการ ปวดศีรษะ ระคายเคืองเยื่อบุ วิงเวียน และอื่นๆ นอกจากนี้ การอภิปรายในบทความยังขยายขอบเขตถึงเรื่องหลักการลดมลพิษในอาคาร อันประกอบด้วย การควบคุมที่แหล่งกำเนิดมลพิษ การระบายอากาศ และการทำความสะอาดอากาศ โดยแต่ละวิธีเน้นถึงพื้นฐานของหลักการ ตัวอย่างวิธีการลดมลพิษในอาคาร และข้อจำกัดของแต่ละวิธี

คำสำคัญ: คุณภาพอากาศในอาคาร, สารอินทรีย์ระเหย, การได้รับสัมผัสมลพิษอากาศของผู้อาศัย, การควบคุมแหล่งกำเนิด, การระบายอากาศ, การทำความสะอาดอากาศ

Introduction

Approximate daily mass intake of fluids by adults was via water consumption (13%) and air breathing (87%)(1). Eighty-eight percent of the total breathing air occurs in indoors, thus obviously indicating that human health risks are substantially prone to poor indoor air quality. A survey of people daily activity in California, USA, also supported that people spent 6% on outdoors, 87% in indoors, and 7% in transit(2). Unsurprisingly, US EPA has ranked poor indoor air quality as one of the US greatest health risk concerns(3).

Indoor air pollutants with significant indoor sources can be generally divided into three classes, i.e., combustion by-products, volatile organic compounds (VOCs), and biogenic particles(4). Combustion by-products of concern include carbon monoxide, nitrogen oxides, sulfur oxides, organic compounds, and particulate matters. Their indoor sources are originated from household activities such as cooking, heating, smoking, and the use of internal combustion devices. In an urban area, some outdoor sources, e.g. traffic, are also regarded as an important source contributing to these pollutants found indoors. VOCs included numerous chemicals with their boiling points falling between 50 °C and 260 °C(5). Well-known examples that are potentially found indoors include benzene, toluene, xylene, styrene, limonene, ethanol, trichloroethylene, tetrachloroethylene, etc. Formaldehyde and acetaldehyde with boiling points below 50°C are usually included in discussion of indoor VOCs as they are commonly found at a significant level in dwellings and offices. Indoor concentrations of many VOCs were found to be 2-5 times greater than those measured outdoors(6-7) and their concentrations varied significantly from one building to another. There are a variety of indoor sources of these VOCs, including building materials, furnishings, office equipment, dry-cleaned clothes, tobacco smoke, cleaning agents, pesticides, etc. The last classified group is biogenic particles, which are particles of biological origin such as bacteria, fungi, virus, dust mites, animal dander, pollen grains, etc.

Exposure to these indoor pollutants may cause adverse health effects, particularly biogenic particles that can result in a number of diseases or allergic responses. Although some of the pollutants such as VOCs are usually found indoors below toxic levels or even below odor thresholds, these levels can cause health symptoms including headaches, mucous membrane irritation, dizziness, and irritability(8). These symptoms are described as "Sick Building Syndromes (SBS)" when the occupants of a building report the symptoms with a rate of over 20%(9). In the United States, Fisk and Rosenfeld(10) estimated that improvement of indoor air quality could save medical cost by $20 billion.

Although research on indoor climate in Thailand has been increasingly received attention during the past decade, there have been relatively a small number of studies related to indoor air pollution and they are limited to some classes of pollutants. The mostly-studied pollutant is particulate matter (PM) of which the studies have been mainly focused on the exposure of people living or working in PM-originating source area or vicinity. Examples of the exposure studies on industrial workers are rock-cutting workers and nearby residential population in Saraburi Province(11-12), workers in textile industry(13), workers in rice mill(14), and workers in sugar mill(15). For non-industrial microenvironments, there are a few studies on PM such as occupant exposure to PM in Bangkok residences(16-18), and commuter exposure in the mass transit system in Bangkok(19). Biological contaminants are another group of indoor pollutants that have been significantly investigated in medical centers(20-23). Due to the prevalence of dust mite-causing allergens, the factors influencing the abundance of dust mite in dwellings have been markedly studied as well as dust mite-related research on medical aspects(24-25).

In indoor air quality research, VOCs have been investigated less in Thailand. One of the possible reasons could be due to availability and accessibility of measurement and analytical instruments. In Thailand, monitoring of outdoor VOCs has been received greater attention than that of indoor VOCs due to large emissions from industrial and transportation sectors. The Pollution Control Department (PCD) regularly monitors ambient VOC levels in Bangkok and vicinity concerning about traffic- and industrial-related health problems. In 2007, the National Environment Board has set the national standard of 9 VOCs in the ambient air, including benzene, vinylchloride, 1,2-dichloroethane (DCE), trichloroethylene (TCE), dichloromethane

(DCM), 1,2-dichloropropane (DCP), tetrachloroethylene (PCE), chloroform, and 1,3-butadiene(26). In contrast to the outdoor VOC monitoring, there have been a few studies related to indoor VOC monitoring in Thailand. The studies included the measurement of VOC concentrations and modeling of VOC distribution in a printing house(27-28), assessment of VOC exposure to Bangkok metropolitan residents(29), measurements of VOC concentrations in public transportation modes in Bangkok(30-31), and investigation of VOCs in Bangkok office buildings(7). These studies show a similar finding that many VOCs detected indoors are considered as hazardous air pollutants according to the Clean Air Act of the United States.

In Thailand, activity pattern of people living in cities is similar to that of western people. A survey of time used by Thai people living in municipal area indicates that the average time spent indoors was 87% of which working or studying time accounted for 9 h (32). Thus, people are exposed to indoor air pollutants most of their daily times. Moreover, most office buildings have been designed to reduce their energy usage by making buildings airtight to minimize loss of the conditioned air because air-conditioning or chilling systems account for a half of the total amount of energy used in a building. As a result, the air quality in buildings with low-ventilation could be worsen, which in turn affect occupant's health and comfort. Mølhave(33) indicated that levels of total VOCs between 0.2 and 3 mg m^{-3} could cause irritation and discomfort. Besides the inadequate ventilation, a number of VOC-emitting sources in buildings can increase the severity of indoor air problems due to their toxicity. Furthermore, the source-originally emitted VOCs, known as primary VOCs, can undergo chemical oxidation with other indoor reactive gases, e.g. ozone, radicals, to form secondary pollutants, which are sometimes even more hazardous than their precursors(34).

Therefore, the objective of this article is to gather research studies associated with investigation of VOCs in non-industrial microenvironments in Thailand. The article is also extended to discuss on principles of VOC reduction in indoors based on the concepts of source control, ventilation, and air cleaning.

Studies on VOCs in non-industrial microenvironments in Thailand

As stated in the introduction, there have been a few studies of indoor VOCs in Thailand during the past decade as compared with those of other indoor pollutants. Among the research studies of VOCs in non-industrial microenvironments, several groups of researchers have measured exposure levels in residences, office buildings, university buildings, and public transportation modes. All studied microenvironments were targeted in Bangkok. Table 1 summarizes the studies that are related to VOCs in non-microenvironment in Thailand categorized by their studied indoor setting types.

Table 1 Studies that are related to VOCs in non-microenvironment in Thailand

Type of microenvironment	Description/Reference
Residences	• VOC measurements in 18 dwellings at roadside and non-roadside(29)
Office buildings and university buildings	• VOC measurements in 17 office buildings(7) • Formaldehyde and acetaldehyde measurements in 12 office buildings(39) • Formaldehyde measurements in an animal preservation room, natural history museum, and chemical storage room in the university(41)
Public transportation vehicles and related studie	• Total volatile organic compound (TVOC) measurements in four public air-conditioned buses in four routes(30) • VOC measurements in air-conditioned buses, non-air-conditioned buses, electric sky trains, and passenger boats(31) • VOC measurements in 60 expressway toll booths(44)

1. Residences

Poolma(29) measured indoor and outdoor levels of VOCs from 18 dwellings located at roadside and non-roadside areas in Bangkok and evaluated the occupant exposure levels during 20th to 27 th July 2005. Types of the selected dwellings were shop houses for roadside areas and detached house and terraces for non-roadside areas. Air samples were collected for 24 h using passive gas tubes containing activated charcoal. They were then extracted with carbon disulfide and analyzed by gas chromatography/mass spectrometry (GC/MS). Sixteen VOCs were detected including benzene(B), toluene (T), ethylbenzene (E), m-, p- and o-xylene (X), 2-ethyltoluene, 3-ethyltoluene, 4-ethyltoluene, 1,3,5-trimethylbenzene, decane, 1,2,4-trimethylbenzene, 1,2,3-trimethylbenzene, 1,4-dichlorobenzene, limonene, and chloroform. However, the use of charcoal as sorbent may have been affected by competitive adsorption among the adsorbates. Non-polar compounds are more preferentially adsorbed onto charcoal than polar compounds, resulting in the displacement of polar compounds in charcoal media(35). Therefore, polar compounds containing oxygen, e.g. alcohols and ketones, were not identified in this study. Most detected pollutants were fallen in an aromatic hydrocarbon class. Among the sixteen VOCs, only six compounds were detected at all sampling sites. They included BTEX, having the average concentrations of 18.9-76.1, 60.2-213, 2.6-15.9, 5.7-26.2, 4.1-21.5, and 3.7-18.9 µg m^{-3}, respectively. The researcher also reported that concentrations of all indoor and outdoor VOCs, except limonene, at roadside areas were higher than those at non-roadside areas. Comparing to oversea studies shows that average concentrations of BTEX measured in Bangkok residences were close to those found in Seoul, Korea(36), but they were 1-2 orders of magnitude greater than those found in Helsinki, Finland(37) and Michigan, USA(38).

The researcher also indicated that the average indoor to outdoor (I/O) ratio of all VOCs was approximately 0.6 for dwellings located at both roadside and non-roadside areas. Unfortunately, this study does not perform a statistical analysis for differences between the indoor and outdoor levels of the measured VOCs, which assists in source identification of the in-residence VOCs. Without the statistical analysis, the I/O result seemed to point to outdoor sources, particularly in polluted areas (e.g. heavy traffic), may be of major contributors to the indoor VOCs. Moreover, most of the selected dwellings were open-entry with highly natural ventilation, which could enhance the infiltration of outdoor pollutants through the building envelopes. However, some of the measured pollutants, i.e. 1,4-dichlorobenzene and limonene, exhibited the I/O ratios nearly close to unity. Thus, the relative importance of indoor sources is not negligible. These two chemicals are used as compositions of normal household products. 1,4-dichlorobenzene is an active ingredient of mothballs, while limonene is used in many cleansing agents, i.e. a citrus fragrance. Although, the researcher suggested that limonene found indoors and outdoors may come from orange trees or flowers, the presence of these trees in Bangkok roads is rarely seen. For the identification of VOC sources for residences in Helsinki, the researcher team adopted principal component analyses to classify sources of VOCs according to their concentration correlations as well as estimation of I/O ratios(37). Their results were relatively different from the Poolma's study(29). Benzene showed the I/O ratio close to unity and its indoor concentrations was attributed to outdoor sources, while toluene, ethylbenzene, and xylenes showed the I/O ratios greater than 1 but less than 5. Both indoor and outdoor sources were identified as contributors to these indoor VOCs. The I/O ratio of limonene was found highest at 17.13, indicating that major sources were from indoors.

Furthermore, the result of the Poolma's study(29) indicated strong relationship of the VOC concentrations between the indoor area samples and personal samples. Their linear correlation coefficient values (r) were 0.699-0.936 at the significant level of 0.05. Thus, the area measurements could be used as an indicator for the significance of occupant exposure to VOCs if suitable personal sampling is not available. However, the accurate estimation of personal exposures still requires personal sampling techniques because people usually move around or spend their time in several microenvironments rather than staying at a fixed location.

2. Office buildings and university buildings

Ongwandee et al.(7) investigated VOCs in 17 office buildings in Bangkok during January to December 2009. The studied buildings had central air-conditioning systems and each floor had 2-5 air handling units (AHU). Indoor and outdoor air samples were collected simultaneously using personal sampling pumps to draw air through sorbent tubes containing Tenax-TA™ resin. Outdoor samples were collected on the same floor as indoor sampling. The samples were then analyzed for 13 target VOCs using thermal desorption (TD) and GC/MS. The target VOCs included hexane, benzene, toluene, ethylbenzene, m,p-xylene, o-xylene, styrene, PCE, TCE, DCE, DCP, chloroform, and limonene. Air exchange rates of the offices were determined by a constant injection technique with hexaflourobenzene as a tracer gas. Results showed that toluene was found to be the most abundant compound among the measured indoor and outdoor VOCs, ranging from 35.3 to 230 µg m^{-3}. This finding is similar to the Poolma's study(29) which indicated toluene was found at the highest concentrations in residences and in the ambient air of Bangkok. Presence of high toluene concentration both indoors and outdoors was attributed to a variety of indoor and outdoor sources such as vehicle emissions, solvent, thinner, printing inks, coatings, adhesives, degreasers, etc. Limonene was also the other most abundant compound found in the offices with the average concentration of 60.6 µg m^{-3}. The major indoor sources of limonene was postulated to be from air freshening spray, vinyl-floor and window glass cleaning agents, and hand-wash alcohol gel. Among the chemical classes detected, the chlorinated compounds were observed to be as low as 0.08-1.10 µg m^{-3}. Thus, occupant exposure to these compounds indoors would be less significant than that occurring outdoors as they are listed on the Thai standard of VOCs in the ambient air(32). In their study, the researchers compared the in-office VOC concentrations with other studies in Asia, Europe, and USA. The average concentrations of benzene, xylenes, and styrene were of the same order of magnitude as those in office buildings in Hong Kong, Korea, India, Finland, and USA. However, toluene in the Bangkok office buildings exhibited a significantly higher concentration than that in other countries, but less than in Singapore. The limonene concentrations in the Bangkok and Singapore buildings were also found nearly four times higher than those found in the Finland and USA buildings.

Estimates of the mean I/O ratios for all target VOCs were greater than unity, ranging from 1.38-24.8. However, only indoor and outdoor levels of BTEX, hexane, TCE, chloroform, and limonene were statistically different at $\alpha \leq 0.05$ level, indicating that in-office sources were important contributors. In contrast to these compounds, the indoor and outdoor concentrations of PCE, EDC, and DCP were not statistically different at the 0.05 level and their I/O ratios were close to unity, identifying that either outdoor sources or indoor + outdoor sources were major contributors. Comparing this study with the Poolma's study(29) in Bangkok residences showed some different result findings. The indoor levels of BTEX in the residences were substantially lower than the outdoor levels, while the indoor BTEX concentrations in the offices were statistically greater than the outdoor concentrations. All studied offices were in the upper floors of the high-rise buildings where the fresh air intakes were from the AHUs on those floors. The influence of any outdoor-ground sources on pollutant infiltration through the upper-floor offices was considered to be less important because of atmospheric dispersion of the ground-emitting VOCs. Moreover, the mean air exchange rate of the offices was as low as 0.29 h^{-1}, indicating that very little fresh air was brought into the buildings. Thus, the predominant contributors to the indoor VOCs were indoor sources such as building materials, office equipment, air recirculation, consumer products, and occupant activities. This is contrast to the indoor and outdoor measurements of VOCs for Bangkok residences(29). In the Poolma's study(29), the selected residences were mostly open-entry. The house ventilation was expected to be substantially higher than the office ventilation. Thus, any potential outdoor sources would possibly contribute to the in-house pollutants that were measured on the ground floor. One of the major outdoor sources was vehicle emissions.

The air exchange measurements revealed a severe problem of indoor air quality in the Bangkok office buildings. Sixteen out of the seventeen studied offices maintained the air exchange rates below the ventilation guideline of the Building Control Act of Thailand. Some of the buildings can be considered as a tight building with the air exchange rates less than 0.1 h^{-1}. The very low ventilation may result from energy conservation measures, which mainly focus on reducing the energy consumption in the buildings. The major part of energy used in these high-rise buildings was air conditioning or chilling systems. The inadequate ventilation can deteriorate the indoor air quality as reflected by a questionnaire survey. The workers reported stuffy bad air and dry air along with a feeling of heavy headed, headache, and fatigue.

Furthermore, the same researcher team(39) investigated levels of formaldehyde and acetaldehyde in the 12 office buildings in Bangkok during March and April 2008. Air samples were collected using cartridges filled with dinitrophenylhydrazine (DNPH) coated silica gel. They were desorbed by acetonitrile and were analyzed with high performance liquid chromatography (HPLC). The mean indoor concentrations of formaldehyde and acetaldehyde were 35.5 and 17.1 $\mu g\ m^{-3}$, respectively. The major sources of formaldehyde and other aldehydes in the offices were likely from furniture made from pressed-wood materials, which are extensive use of urea-formaldehyde and melamine-formaldehyde resins as hot-press adhesives. One of the studied offices was found to have significantly high formaldehyde concentration of 98.4 $\mu g\ m^{-3}$. The survey result indicated this office was carpeted and the interior walls were covered by plywood. One-fourth of the office space was occupied by the particleboard shelves. The extensive use of plywood and particleboard in this office could contribute to the high level of indoor formaldehyde. The average indoor to outdoor ratios were 3.5 for formaldehyde and 5.7 for acetaldehyde.

The ratios above unity point to indoor sources were of important contributors to the high indoor levels. Environmental tobacco smoke (ETS) is also one of the most important indoor sources of carbonyls. However, smoking is not allowed in office buildings, government buildings, and public places(40). As a result, the measured concentrations of formaldehyde and acetaldehyde in the Bangkok offices were found relatively lower than those measured in the smoking offices in the overseas studies.

Another formaldehyde-monitoring study was conducted by Sriprasertsuk(41). The researcher investigated indoor levels of formaldehyde in three rooms of the buildings in Chulalongkorn University. The selected rooms were an animal preservation room, natural history museum, and chemical storage room. All three rooms were involved in use of formaldehyde solution. Air samples were collected from July to December 1997. The air sampling and analysis methods were similar to those given in the study of Ongwandee et al.(39). The highest level of formaldehyde was found in the animal preservation room, ranging from 0.120 ppm (159 $\mu g\ m^{-3}$) to 0.295 ppm (390 $\mu g\ m^{-3}$). This room had open containers filled with formaldehyde solution (formalin), which were responsible for the significant release of formaldehyde into the room air. Comparing with the measured formaldehyde in the office buildings(39) indicated that the concentrations in the animal preservation room far exceeded those found in the typical offices. Meanwhile, formaldehyde levels in the museum and chemical storage room varied from non-detectable to 0.010 ppm (13.2 $\mu g\ m^{-3}$), except for the staff-member room as a part of the museum that had the concentration up to 0.018 ppm (23.8 $\mu g\ m^{-3}$). The staff-member room was also used to store reserved tanks of formalin and the size of the room was smaller than the museum. Thus, it was not surprising to detect such a high level of formaldehyde in the staff room. The measured formaldehyde concentrations did not exceed the time-weighted average (TWA) concentration of 3.0 ppm (3960 $\mu g\ m^{-3}$) by the Thai occupational safety and health regulation(42). However, exposure to formaldehyde can cause irritant effects, sensitization and asthma, and carcinogenicity(43). Expectedly, the staff members of the animal preservation room reported eye irritation. The researcher also performed a test by increasing the ventilation of the animal preservation room with a mechanical fan for 30 min. The formaldehyde concentration was decreased by 32%.

3. Public transportation and related studies

Public transportation modes are the other microenvironments that have been received attention due to commuter exposure to VOCs while travelling on severe traffic roads in Bangkok. The National Statistic Office(32) reported that people in Bangkok spent an average of two hours commuting from home to work and back in 2004. Commuters are inevitably exposed to in-vehicle air pollutants. Despite the outdoor sources from traffic emissions, the in-vehicle sources of origin are of importance. There are a variety of in-vehicle sources of VOCs, including car interiors (e.g. seats, cushions, wall, and curtains), occupant-related sources (e.g. personal care products, commuter belongings, and exhalation), fuel leakage from a storage tank, and air recirculation system in a case of air-conditioned vehicles. There have been two studies investigating VOCs in public transportation modes as described below.

Feungpean and Chinwetkitvanich(30) measured total VOC (TVOC) levels in four public buses while cruising four routes in Bangkok. Three of the selected air-conditioned buses were new and manufactured in the same year of 2007, while the other bus was manufactured in 2001. Air samples were collected for one day during 9 a.m. to 11 a.m. using charcoal tubes and they were then analyzed by thermal desorption and gas chromatography / flame ionization detector (TD GC/FID). The levels of TVOC in the new buses ranged from 2.41 to 3.74 mg m^{-3}, while the concentration in the old bus was 1.40 mg m^{-3}. Although the researchers did not perform a statistical relation of the TVOC concentrations and bus ages due to a few numbers of data, they observed that all new buses exhibited the significantly higher concentrations than did the old bus. Moreover, the highest concentration was found in the bus with the in-cabin highest temperature. They postulated that the important sources could also be from potential in-bus sources such as automotive trims. However, source identification for the in-cabin VOCs was not conducted in this study. Thus, outdoor sources (e.g. traffic emissions) or indoor+outdoor sources may be responsible for such these high TVOC concentrations.

Ongwandee and Chavalparit(31) investigated VOC concentrations in four public transportation modes in Bangkok during two rush hour periods (7:00–9:00 a.m. and 4:00–7:00 p.m.). The four modes included air-conditioned buses, non-air-conditioned buses, electric sky trains, and passenger boats traveling along the canal. The target VOCs were benzene, toluene, ethylbenzene, and m,p-xylene (BTEX). Air samples were collected using charcoal tubes. The sorbents were extracted with carbon disulfide and analyzed for BTEX by GC/MS. Measurements show that the in-cabin concentrations were varied significantly among transportation modes and travelling routes. The mean concentrations of all studied vehicles ranged from 10.9 to 82.9 µg m^{-3} for benzene, 39.5 to 503 µg m^{-3} for toluene, 0.5 to 24.6 µg m^{-3} for ethylbenzene, and 1.0 to 97.1 µg m^{-3} for m,p-xylene. The BTEX concentrations measured in buses were found to be highest, while the concentrations in sky train were lowest which may partially be due to its elevation of the tracks above the traffic. As a result of the strong wind during cruising, the BTEX levels in boats with natural ventilation were not as high as those of the buses. The traffic density was observed to influence in-bus levels of BTEX as the air-conditioned and non-air-conditioned buses on the less traffic route appeared to have lower concentrations. Besides the traffic emission source, in-bus sources may also contribute to the significantly high levels of air pollutants as two of the studied air-conditioned buses exhibited the toluene concentrations greater than 1 mg m^{-3}. The high concentrations found in air-conditioned buses were similar to the measurements conducted by Feungpean and Chinwetkitvanich(30) with the high TVOC levels in the air-conditioned buses. Unfortunately, the relationships between the in- and out-cabin concentrations of the air conditioned buses were not performed to determine relative strength of sources in this study. As comparing to the fixed site monitoring at the traffic roadside conducted by the PCD, the in-bus mean concentrations of BTEX were 3.0-4.7 times higher than the ambient 24-hour average concentrations. Thus, the roadside monitoring may not be able to reflect the actual commuter exposure levels of VOCs as the measured 24-hour average concentrations were far below the rush-hour concentrations. Moreover, the average in-bus concentrations of BTEX in Bangkok were substantially greater than those in oversea studies such Hong Kong (China), Guangzhou (China), Detroit (USA), and Taegu (Korea). Particularly, benzene and toluene concentrations were 3-23 times higher than those studies.

Chuamuangphan(44) studied the relationship between indoor air quality and work-related illness among the collectors who worked in expressway toll booths in Bangkok and vicinity. Carbon monoxide (CO), carbon dioxide (CO_2), PM less than 10 micron (PM_{10}), and VOCs were monitored inside and outside 60 toll booths during September to November 2008. A questionnaire was used to evaluate work-related illness among the expressway toll booth collectors. It included three parts, i.e., general data of a respondent, workplace environment, and illness history and health conditions. The number of respondents was 180. Results indicate that levels of in-booth and out-booth PM_{10} correlated with respiratory illness, while CO_2 and CO correlated with headache; VOCs correlated with stress at the significant level of 0.05. As expected, the strong correlations between the in-booth and out-booth pollutant levels were observed and the in-booth levels also correlated with the number of vehicles on the roads. However, CO_2 did not exhibit correlation with the pollutant concentrations since CO_2 is mainly originated from occupant exhalation. Its indoor concentration is usually taken as a surrogate for other occupant generated pollutants such as bioeffluents, and it is used for estimation of a ventilation rate per occupant(45). It is noted worthy that some booths exhibited the CO_2 level above 1000 ppm, which exceeded the recommended indoor CO_2 of 1000 ppm by American Society of Heating, Refrigeration and Air Conditioning Engineers(46) (ASHRAE). The high CO_2 concentration evidently indicated the insufficient ventilation of the toll booths.

Mitigation of indoor VOCs

Mitigation of indoor air pollutants is technically categorized into three principles: (i) source control, (ii) ventilation, and (iii) air cleaning(43). Below are descriptions of the three principles.

1. Source control

Source control is a theoretically desirable way to control pollutants at their sources before they are emitted to indoor air. Source control consists of various applications, which are dependent on characteristics of particular pollutants. Examples of source control applications are: (1) avoidance of the entry of VOC-originating material, e.g. building materials, furnishings, consumer products, combustible devices, cleaning agents etc., and (2) avoidance of VOC-releasing activities, e.g. smoking, burning incense and candles, etc. They can be performed by physical removal of the sources or replacement with non-emitting or low-emitting products such as avoidance of wood products made from hardwood plywood and particle board with typically containing urea-formaldehyde resins(39). Use of other acceptable substitutes is advisable such as softwood plywood, waferboard, iso-board, and phenol-formaldehyde (P-F) bonded particleboard. Another advisable application is use of water-based paint instead of oil-based or solvent-based paint. Unfortunately, the source control applications have been drawn little attention in Thailand. This is likely because people are unaware of chronic health effects resulting from long-term exposure to low odor thresholds of VOCs indoors. The government can play a major role in this practice by initially launching voluntary campaigns such as a “low emission rate” label for indoor furniture, building materials or cleaners.

2. Ventilation

Ventilation is intended to remove heat or moisture or to reduce levels of indoor air pollutants. Ventilation may occur naturally by infiltration as a result of flow of outdoor air through unintentional or intentional openings in the building envelope(43). In past decades, most high-rise buildings in Bangkok have been designed to provide year-round climate control through mechanical ventilation system. The primary purpose of mechanical ventilation is to provide a comfortable indoor environment for building occupants. An additional purpose is to reduce contaminants of indoor origin as well. Although mechanical ventilation was found in efficient removal of respirable dust when outdoor particle levels were relatively low(47), several studies showed inconsistent results in reducing indoor VOCs. Godish(43), in a review of the effect of mechanical ventilation on formaldehyde levels, reported a non-linear correlation. As the ventilation increases, its effectiveness in reducing formaldehyde levels decreases. This phenomenon was explained by the increased desorption of formaldehyde on material surfaces into room air as increasing the ventilation. Hodgeson et al.(48) also indicated a similar phenomenon possibly responsible for an increase of indoor acetaldehyde and hexanal levels as increasing the building ventilation. The study of Ongwandee et al.(49) on the effect of ventilation on 13 VOCs in Bangkok’s buildings showed that the air exchange rates did not linearly correlate with the levels of individual VOCs at a $p<0.05$. This suggested that any factor other than ventilation is also influencing levels of indoor VOCs at the same time. An important related-ventilation concern is attributed to inadequate ventilation in buildings with air-conditioning system. Ongwandee et al.(7) reported that sixteen out of the seventeen studied buildings in Bangkok did not comply with the ventilation guideline regulated by the Building Control Act of Thailand. Particularly, five buildings had extremely low ventilation, which was below 0.05 h^{-1}. The reason for operating the buildings with very low ventilation may be due to energy saving measures by reduction of the loss of conditioned air.

3. Air cleaning

The last practice is air cleaning, which is used when the two previous measures are insufficient; for example, the ventilation method is limited by weather conditions or high levels of contaminants outdoors.

Portable air cleaning devices are becoming more and more popular in households and offices. They can be classified into three types according to types of pollutants being removed and their removal mechanisms(50). These include particle removal, gaseous pollutant removal, and pollutant destruction. Air cleaners with the purpose of VOC removal employ gas-phase air filters such as activated carbon, which adsorbs the gaseous pollutants. However, these filters have several implementation considerations. They are specifically designed to remove certain gaseous pollutants, not all of the pollutants present in the room air. Moreover, these adsorbent filters are also limited by their adsorption capacity, thus resulting in a temporary removal basis. For the pollutant destruction application, photocatalytic oxidation (PCO) cleaners are intended to destroy gaseous pollutants, e.g. VOCs, by converting them into harmless gases (e.g. carbon dioxide and water). However, the application for homes is still limited because available catalysts are ineffective in destroying indoor gaseous pollutants(50). Instead, PCO may convert gaseous pollutants into more harmful pollutants due to incomplete oxidation reactions.

Conclusions

The review of the previous studies on indoor air pollution in Thailand indicates that indoor air in many non-industrial microenvironments have been contaminated with a variety of VOCs to different degrees. The key factors influencing levels of VOCs are most likely due to inadequate ventilation (e.g. the office buildings), indoor VOC-originating sources (e.g. the office buildings and the certain rooms with specific use in the university), and outdoor VOC-originating sources (e.g. traffic and residences near the roadsides). However, there are still lacking studies in other types of indoor settings, particularly for public access buildings in where many people spend their time during the day. These microenvironments include schools, hospitals, government buildings, bus stations, department stores, and restaurants. Generally, the resulting data are needed to further evaluate the correlations with occupant exposure and health risks or occurrences of a variety of illness symptoms. Finally, the broad-base scientific results will support development of regulatory consensus to help preventing people exposure to these indoor pollutants and to improve the indoor environments. Furthermore, there still needs various studies of indoor air chemistry and kinetics, which will provide a better and deep understanding of the dynamic behaviors of airborne pollutants indoors. Although many researchers in overseas have been investigating indoor pollutant interactions, transformation, transportation, and chemistry-related aspects, we still require these kinds of studies being conducted in Thailand. The differences in the indoor setting characteristics and occupant activities between overseas countries and Thailand may result in different findings, which are relatively unique to our country.

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