The Health Risks of Airborne Polycyclic Aromatic Hydrocarbons (PAHs): Upper North Thailand

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Abstract
Every year, Northern Thailand faces haze pollution during the haze episode. The particulate matter (PM), including fine fraction (PM2.5), a coarse fraction (PM2.5–10), and 16 polycyclic aromatic hydrocarbons (PAHs), was measured in six provinces in upper north Thailand during the haze and non-haze episodes in 2018. Eighty-three percent of the PM2.5 measurements (21.8–194.0 µg/m3) during the haze episode exceeded the national ambient air quality standard in Thailand. All 16 PAHs were detected in the study area in both periods. The average concentration of total PAHs (particle-bound and gas-phase) during the haze episode was 134.7 ± 80.4 ng/m3, which was about 26 times higher than those in the non-haze (5.1 ± 9.7 µg/m3). Naphthalene and acenaphthene were the dominant PAHs in the gas phase; whereas, indeno[123-cd]pyrene, benzo[a]pyrene, and Benzo[ghi]Perylene were dominant in the particle-bound phase. The estimated inhalation excess cancer risk from PAHs exposure was 9.3 × 10−4 and 2.5 × 10−5 in the haze episode and non-haze, respectively. Diagnostic ratios and principal component analysis revealed that PAHs were derived from mixed sources of vehicle emission and solid combustion in the haze episode and vehicle emission in the non-haze period. High pollution levels of PM and large cancer risk attributable to the exposure of PAHs in the haze episode suggest urgent countermeasures to reduce the source emission, especially from the solid combustion in the area.

Plain Language Summary
Northern Thailand has been faced with air pollution every year, particularly in the dry season. The concerning pollutant is particulate matter (PM), namely: fine particle (PM2.5) and coarse particles (PM2.5–10). Some hazard substances were contaminated in the air and also bounded inside PMs like polycyclic aromatic hydrocarbon (PAH), some of them are classified as harmful to human health. This study investigated the PM2.5 concentrations and PAHs in the upper north of Thailand. PM2.5 concentrations was exceeded the national ambient air quality standard of Thailand in dry period so-called haze period, moreover, PAHs concentration on haze period was 26 times higher than the non-haze period. This research indicated that cancer risk due to PAHs exposure during the haze period was 9.3 × 10−4 whereas it was 2.5 × 10−5 in the non-haze period. The findings of this research will be scientific information supporting the local government to provide intervention or mitigation measures to reduce air pollution or preparedness response plan.

1. Introduction
Air pollution is identified as a critical role in human health in both urban and rural areas. Globally, it also caused the significant effects on the economic, social, and environment. An extensive range of global studies has been conducted on almost all aspects of air pollution, including a specific type, quantification of emissions, and assessing its various impacts (J. Chen et al., 2017). Cheong et al. reported that the trans-boundary haze problem had seasonally occurred in Southeast Asia (Cheong et al., 2019). Typically, haze in this region was determined by particulate matter (PM) concentration. However, the PM is formed by different particle types, both solid and liquid form with various physical and chemical properties (Fang et al., 2009). PM mainly contributed to the air pollution in Thailand (Kliengchuay et al., 2021; Ruchiraset & Tantrakarnapa, 2018, 2020). The components of the particles are dust, dirt, soot, smoke, ash, and aerosols (Lina, 2012). The causes of PM have been identified from both natural and anthropogenic sources, such as fuel combustion, industrial emission, forest fire, and biomass burning. Biomass burning can also increase
the PM concentration in environments that expand outdoor and indoor in both urban and rural areas as well as developed and developing countries (Johnston et al., 2019).

The Upper North of Thailand (UNT) consists of eight provinces, namely, Chiang Rai, Chiang Mai, Nan, Phayao, Phrae, Mae Hong Son, Lampang, and Lamphun. The main areas are mountainous, followed by agricultural components. A variety of crops can be observed in these areas, namely, paddy field, maize, sugar-cane, soybean, and the like. These agricultural products have been the significant contribution of Thailand, which is exported to other regions. We observed that many farmers also burnt their agricultural residuals in their farms after harvesting. In 2018, the Bank of Thailand reported an increasing ratio of croplands in the northern part: 38% of rice, 22% of sugar cane, and 12% of maize (Bank of Thailand, 2019). The biomass burning from agricultural areas might induce forest fire. Usually, haze episodes occur during the summer season and harvesting period of agriculture (February to April). The concentration of PM$_{2.5}$ and PM$_{10}$ were higher than the Thailand ambient air quality standard under the Pollution Control Department. The acceptable daily average concentration for PM$_{2.5}$ and PM$_{10}$ should be less than 50 and 120 µg/m$^3$, respectively (Kliengchuay et al., 2018).

In general, the seasonal haze arises from combustion-associated smoke emissions, which is comprised of high concentrations of PM fine enough to be airborne (Cheong et al., 2019; Zhang et al., 2017). Many researchers had reported the relation of health with PM; they have contributed to the health impacts in terms of acute or chronic effects (Y.-C. Chen et al., 2016). The PM can adsorb toxic substances; in particular, polycyclic aromatic hydrocarbons (PAHs) are bound on PM. Most PAHs were diffused in environments that were formed during incomplete combustion or pyrolysis of organic material (Srogi, 2007; Yin & Xu, 2018; Zhang et al., 2019). PAHs can exist in the form of semi-volatile compounds in both gas and particulate (through condensation/adsorption) phases (Y.-C. Chen et al., 2016). Typically, PAHs concentration existed in particulates that were mainly established by emission sources (Yin & Xu, 2018). Many PAHs are toxic, mutagenic, and teratogenic. Some of them are classified by the International Agency for Research on Cancer as known, possibly or probably carcinogenic to human (Abdel-Shafy & Mansour, 2016). The most significant health effect, lung cancer, to be expected from inhalation exposure to PAHs (K.-H. Kim et al., 2013). In addition, some PAHs including pyrene, benzo(a)pyrene, and naphthalene can induce skin inflammation and skin sensitization (Murawski et al., 2020). PAHs are listed in the priority carcinogen family, in the environment, in France and in Europe. Gaseous PAHs tend to be less toxic than particulate PAHs, which are ranked as possible or probable human carcinogens (Maitre et al., 2018).

Recently, UNT has suffered from high air pollution, especially PM$_{10}$ and PM$_{2.5}$. However, many studies have focused on the PM concentration and their bound PAHs in different areas (Chantara et al., 2010; Janta et al., 2020; Pongpiachan et al., 2015; Wiriya et al., 2013). Some researchers carried out a health risk assessment. A comparative study of particle-bound PAHs concentrations in various locations of Thailand has not been undertaken. In this study, we collected samples of PM$_{10}$ and PM$_{2.5}$, PM-bound, and gaseous phase PAHs in the rural and urban areas of six provinces in UNT. Moreover, we also focused on the sources of PAHs and their cancer risk. The results of this study will benefit further intervention and mitigation measures to reduce the health impact of PAHs. Furthermore, the obtained scientific information can be beneficial to involved organizations in the setting up of strategic plans to minimize health impacts.

2. Materials and Methods

2.1. Sampling Location

Twelve sampling sites located in six provinces in the northern part of Thailand are Chiang Rai, Mae Hong Son, Nan, Lampang, Lamphun, and Tak. The urban (I) and rural (II) locations were selected as representative sites for each province (Table S1 in the supporting information). Most of the urban sampling sites were surrounded by residential and commercial areas, whereas the rural sites were residential areas and paddy fields. All of the sampling sites were located near the traffic road with the distance of the nearest road varied from 17 to 136 m. There was only one sampling site, the urban site of Lamphun province, located 1.5 km far from the industrial estate. The station was located in the West direction of industrial estate.
2.2. Sampling Method

PM$_{2.5}$ (fine fraction), PM$_{2.5-10}$ (coarse fraction), and PM-bound PAHs samples were collected by polytetrafluoroethylene (PTFE) filter using a Deployable Particulate sampler (DPS) (SKC, Eighty-Four) with a flow rate of 10 L/min. A 37 and 47-mm PTFE filters were used for PM$_{2.5}$ and PM$_{2.5-10}$ samples, respectively. The filters were cleaned with acetone and kept in the desiccator cabinet until stable weight. PAHs in the gas phase were collected by amberlite XAD-2 resins. PM and PAHs samples were simultaneously collected in 24 h at each sampling location for 3 days. The sampling period for the haze episode was conducted in March 2018 and for the non-haze period in July 2018 (Table S1). Due to the limitation of the number of air samplers and scientist technicians, we can perform simultaneously sampling only for the same province. Also, we designed the sampling period as short as we can which can be finished within 2–3 weeks for each period.

2.3. Extraction and Analytical Procedure

The PM$_{10}$ and PM$_{2.5}$ concentrations were determined using a gravimetric method with the use of an ultra-microbalance with a readability of 0.1 μg (Sartorius MSU2.7S-000-DF Cubis Ultra Micro Balance). The PM-bound and gas-phase PAHs samples were extracted in a 10 ml acetonitrile (HPLC grade) for 30 min using an ultrasonicator (Crest) at ambient temperature. The extracted solutions were then filtered through a 0.2 μm PTFE syringe filter and added 20 μl dimethyl sulfoxide to prevent volatilization. The solution was then evaporated by a pure N$_2$ gas evaporator with a heating block and a control temperature of 35°C, and the volume was adjusted to 50 μl by (60:40) acetonitrile, DI water.

The extraction and analytical procedure of PAHs were applied from the study of Baugadaeng (2019) and NIOSH manual method 5506 (NIOSH, 1994). Sixteen PAHs were analyzed by HPLC coupled with two detectors, fluorescence and UV (Shimadzu, SPD-M20A). SUPELCOSIL™ LC-PAH HPLC column (ID, 25 cm × 4.6 mm; 5.0 μm) was used for stationary phases, while acetonitrile (HPLC grade) were used for mobile phases. The standard analytical solution utilized in this study was PAHs Calibration Mix of 10 μg/ml in acetonitrile manufactured by Supelco Inc. The standard curve was drawn from a series of five concentrations of mixed standard PAHs diluted in acetonitrile, including 0.625, 1.25, 2.50, 5.00, and 10.00 mg/L. The calibration curve $R^2$ range of 16 PAHs was 0.9985–0.9999. The limit of detection was calculated from a variety of PAHs concentration mixed standard for 10 replicates. The recovery test was implemented to determine the efficiency of the extraction method for the particle-phases and gas-phase PAHs. A 37 and 47-mm PTFE filters and XAD-2 washed resin adsorption tube were spiked with a known concentration PAHs standard solution. The PAHs were extracted by the same method as the sample for 10 replicates. Detection limits and recovery of PAHs are shown in Table S2.

2.4. Data Analysis

Descriptive statistics were used to explain the concentration of the pollutants namely; minimum, mean, standard deviation, median, first quartile, third quartile, and maximum. Student’s t-test was used to determine the difference of the concentration in particle-bound versus gas phase and haze versus non-haze period. The diagnostic ratio (DR) calculation had used ratios of BaA/(BaA + CHY) and Ind/(Ind + BgP) to diagnose the possible sources of the detected PAHs bound in PM$_{2.5}$. The principal component analysis (PCA) statistical analysis was computed using the Statistical Package for Social Science version 18 (SPSS), Mahidol University license. PCA was computed using varimax rotation, a Kaiser-Mayer-Olkin Measure of sampling with an adequacy value of >0.5 for suitable show factor analysis, and Bartlett’s test of sphericity is less than 0.05, significantly.

2.5. Health Risk Assessment

The inhalation cancer risk of PAHs was calculated according to the approach developed by the Office of Environmental Health Hazard Assessment of the California Environmental Protection Agency (CalEPA) (Jia et al., 2011; OEHHA, 2003). The toxicity of PAHs was presented in terms of their most toxic form, BaP. The toxicity of BaP equivalency (BaP$_{eq}$) was used to assess carcinogenic health risks in several studies (Khan et al., 2015; Pongpiachan et al., 2015; Sulong et al., 2019). The BaP$_{eq}$ was computed by multiplying
PAHs concentration with the toxicity equivalency factor (TEF) of individual PAHs compound by using Equation 1.

$$ECR = \sum BaP_{eq} \times UR_{BaP}$$

(1)

$C_i$ was the concentration and TEF is the toxic equivalency factor of the $i$th PAH congener. The TEF of 0.001 was for NAP, ACY, ACE, FLU, PHE, FLT, and PYR. The TEF of 0.01 was for ANT, CHY, and BgP. The TEF of 0.1 was for BaA, BbF, BkF, and InD. The TEF of 1 was for BaP and DaA (Nisbet & LaGoy, 1992).

The excess cancer risk (ECR) was calculated by the product of $\sum BaP_{eq}$ and the unit risk of BaP (UR$_{BaP}$), as in Equation 2. The unit risk factors, in the units of inverse concentration as nanograms per cubic meter was used to assess cancer inhalation risk directly from air concentrations (Jia et al., 2011; Khan et al., 2015; Pongpiachan et al., 2015; Sulong et al., 2019). UR$_{BaP}$ was provided by the World Health Organization which lifetime risk of respiratory cancer of $8.7 \times 10^{-5}$ per ng/m$^3$ (Pongpiachan et al., 2015; World Health Organization, 2000) was used for the calculation in this study.

$$\sum BaP_{eq} = \sum_{i=1}^{n-1} (C_i \times TEF_i)$$

(2)

3. Results and Discussion

3.1. The Comparison of PM and PAH Concentrations in Haze and Non-Haze Period

The measurements of PM and PAH concentrations in this study are shown in Table S3. There were 83% of the PM$_{2.5}$ measurements in the haze episode, exceeding the Thailand national ambient air quality standard (50 µg/m$^3$); whereas, all the measurements in the non-haze episodes were in accordance with the standard. The average concentration of PM$_{2.5}$ (fine fraction) in the haze episode was $105.3 \pm 44.8$ µg/m$^3$, which was about 7 times higher than in the non-haze ($14.2 \pm 14.1$ µg/m$^3$). Also, the average concentration of the coarse fraction (PM$_{2.5-10}$) in the haze episode ($30.2 \pm 19.1$ µg/m$^3$) was significantly higher than those in the non-haze ($19.3 \pm 19.8$ µg/m$^3$) with $p$-value less than 0.001. The average concentration of total PAHs (PM-bound and gas-phase) in the haze episode was $134.7 \pm 80.4$ ng/m$^3$, which was significantly higher than (about 26 times) those in the non-haze ($5.1 \pm 9.7$ µg/m$^3$). In the haze episode, the average concentration of gas-phase PAHs ($90.5 \pm 59.3$ ng/m$^3$) was significantly higher (2 times) than PM-bound PAHs ($44.2 \pm 28.4$ ng/m$^3$). Twenty-seven times the PAHs concentration were bound in the fine fraction ($42.7$ ng/m$^3$) that significantly higher than the coarse fraction ($1.6$ ng/m$^3$) during haze episode; however, there was a same concentration in the non-haze episode ($0.9$ ng/m$^3$).

The average total concentration of PAHs (PM-bound and gas-phase) and PM$_{10}$ (sum of PM$_{2.5-10}$ and PM$_{2.5}$) are shown in Figure 1. The highest average of PAHs concentration during the haze episode was found in the urban area of Mae Hong Son province ($267.3 \pm 4.8$ ng/m$^3$); whereas, the highest concentration during the non-haze was found at the rural area of Tak province ($36.9 \pm 7.4$ µg/m$^3$). The highest concentration of PM$_{10}$ during the haze and non-haze episodes was found in the rural area of Tak province ($217.5 \pm 26.9$ µg/m$^3$) and the urban area of Tak province ($115.4 \pm 10.8$ µg/m$^3$), respectively. A low concentration of PAHs and PM$_{10}$ was found at Nan Province during the haze episode. In most of the provinces, the concentration of PAHs in the urban area was higher than that in the rural area, except for Tak province. The high concentration of PM$_{10}$ and PAHs was found in Tak province during the non-haze episode.

PM concentration in Northern Thailand measured in this study was higher than those in the previous studies both in haze and non-haze period (Chantara et al., 2010; Janta et al., 2020; Pongpiachan et al., 2015; Wiriy et al., 2013) (Table S4). This study was the first measurement of gas-phase PAHs in Thailand. During the haze episode in Northern Thailand, the total PAHs measured in 2018, as stated in this study, was about 5–50 times higher than the previous measurement during years 2006–2016. In the non-haze, the concentration of PAHs presented in this study was slightly higher than those in previous studies. This finding indicated the severity of the haze situation in Northern Thailand, and the toxicity caused by exposure of PAHs might be at a severe level. Compared to other Asian countries, PAHs in the haze episode in this study was about 1.5–5 times higher in Xi’an and Seoul (Bandowe et al., 2014; J. Y. Kim et al., 2012) (Table S4).
All 16 PAHs were detected in the study area. PM-bound and gas-phase PAHs are shown in Table S5. For both periods, the haze episode and non-haze, the low molecular weight of PAHs (i.e., NAP, ACY, ACE, and FLU) were detected only in the gas phase. In contrast, the high molecular weight of PAHs (i.e., BbF, BkF, BaP, DaA, BgP, and InD) was detected only in the PM-bound phase. Some PAHs with moderate weight (i.e., PHE, ANT, FLT, PYR, BaA, and CHY) were detected in both gas-phase and particle-bound phases. These results were approximate to Kawichai et al. studies (Kawichai et al., 2020). The low molecular weight PAHs with high vapor pressure would tend to be associated with particles, while the high molecular weight with low vapor pressure will be found in the gas phase (Abdel-Shafy & Mansour, 2016). Particle-bound PAHs during the haze episode were more absorbed on the fine fraction (75%–100%), compared to the coarse fraction. This result was similar to previous studies that particle-bound PAHs were higher in the fine fraction (Manoli et al., 2002; Vardar & Noll, 2003). NAP and ACE were the dominant PAHs in the gas phase during both haze and non-haze episodes. InD and BaP were the dominant PAHs in the PM-bound phase during the haze episode, whereas, BaP and BbF were the dominant PAHs in the PM-bound phase during the non-haze episode. The composition profile of PAHs at the sampling sites during the haze and non-haze episodes and are shown in Figure 2. NAP (23%–73%) and ACE (7%–54%) were the dominant PAHs at most of the sampling sites. The average proportion of NAP and ACE for all stations of 32% and 19%, respectively, in the haze episode and 42% and 15%, respectively, in the non-haze period. This study found InD, BaP, and BgP were the dominant compound in PM$_{2.5}$-bound PAHs during the haze episode. Compared to other studies in Thailand, different compounds were dominant at different locations and sampling periods that might be
dependent on the sources of PAHs. For example, PHE and BgP were the dominant compounds at Tak Province (Janta et al., 2020), BbF and BkF were dominant at nine provinces of Northern Thailand (Pongpiachan et al., 2017), and FLT and PYR were dominant at Chiang Mai (Kawichai et al., 2020).

3.3. Sources of PAHs

3.3.1. Diagnostic Ratios

The PAHs profile was identified from a possible pollution source (traffic, biomass combustion, or petrogenic vapor) by a DR with a couple of individual PAHs species (Akyüz & Çabuk, 2010; Ravindra et al., 2008; Yunker et al., 2002). In previous studies, the particulate phase PAHs was commonly group for diagnosis ratio (Ravindra et al., 2008; Rosario et al., 2005) because there were founded in environment and be affected from photodegradation less than gas phase (Tobiszewski & Namieśnik, 2012). However, the diagnosis ratio is a method for PM source identifying, thus we considerate to focus on particulate PAHs which have enough

**Figure 2.** Composition profiles of PAHs for particle- and gas-phase PAHs during haze episode and non-haze.
various species data in both seasons for additional information to source identified on our study area. The determination of BaA-CHY and Ind-BgP ratios are mostly coupled with investigating a source of the fine particle (Yunker et al., 2002). The ratio of Ind/Ind + BgP in a fine particulate can determine a major source from petroleum combustion by a ratio of less than 0.50 and determine the primary source for biomass/coal combustion by a ratio more than 0.50. Nevertheless, the ratio of BaA/BaA + CHY was used to determine the source the same as Ind/Ind + BgP ratio. The most of fine particulate is generic from vehicle emission when the ratio is more than 0.50. The diagnosis ratio of PM$_{2.5}$-bound PAHs in this study was plotted against both ratios for clear source determining (Yunker et al., 2002). The results suggest that the PAHs were derived from mixed sources of vehicle emission and solid combustion in the haze period, and it may come from vehicle emissions in the non-haze period.

In Figure 3, the ratio of Ind/Ind + BgP was precise that particle-phase PAHs in ambient are possibly observed from a mixed source. The ration ranged between 0.23 and 0.58: Nineteen samples were more than 0.50, and 12 samples were less than 0.50. It identified that the fine particulate in the haze episode might mostly come from biomass combustion. The BaA/BaA + CHY ratio ranges support the previous result that the primary source is the mixed source by a ratio that was plotted between 0.30 and 0.50. On the other hand, the ratio of Ind/Ind + BgP in the non-haze episode showed particle-phase PAHs possibly from vehicle emission. Although the number of samples was less because individual PAHs species were non-detectable (lower than detection limit value), most of the ratio results were plotted near 0.50 and over. Thus, it may define that the fine particle on the studied area came from mixed sources in the haze episode (mostly from solid combustion). In contrast, the fine particle in the non-haze may come from vehicle emission. However, upon considering the results of only the haze episode for the different sites between rural and urban areas, it was found that ratios of Ind/Ind + BgP and BaA/BaA + CHY showed a different major source of fine particulate.

As shown in Figure 4, most of the ratios in the haze episode on rural sites were plotted on mixed source range, and some of them were plotted on the vehicle emission. In contrast, a ratio on urban site was plotted on both vehicle emission and mixed sources similarly. The dominant source of PAHs on rural sites might have been biomass combustion more than vehicle emission. It was different from the urban site where a major source is the mixing of traffic pollutants and biomass combustion.

### 3.3.2. Principal Component Analysis

The data were analyzed for the haze and non-haze episodes, as illustrated in Table S3. As shown in the component data in the haze episode, the contribution was mostly due to Phe, BaA, BaP, Chr, BbF, Pry, BkF, BgP, Acy, Flt, Flu, and Ant for the dominant component. In the non-haze period, the dominant component was almost the same as in the haze episode, but it showed different individual PAHs as DaA shown only in the non-haze period, and there have no Ant and Pyr. In summarized data, the strongest component in the
non-haze season was BkF, InD, and BgP (0.942, 0.924, and 0.903, respectively), which were traffic-related PAHs sources (Harrison et al., 1996; Simcik et al., 1999). Although the traffic-related PAHs of BkF, InD, and BgP were shown in the haze period (Harrison et al., 1996; Simcik et al., 1999), the PAHs related to coal/biomass combustion source were also shown as strong components for Pyr (shown only in this period), Flua was shown in both periods. However, the loading value in the haze period was more than in the non-haze period. From the data collected, it can be considered that the PAHs in the north of Thailand may represent a mixed source of biomass combustion and traffic. However, some PAHs species may appear as a dominant or increase loading, such as Pyr, Flua, and Chr in haze period, and it may illustrate that biomass combustion pollution is higher in this period while the traffic-related PAHs (BkF, InD, and BgP) are dominant species in the non-haze period.

3.4. Health Risk Assessment

The estimated inhalation ECR in this study was presented in Table S2. The average $\Sigma$BaP$_{eq}$ was 10.6 and 0.3 ng/m$^3$ in the haze episode and non-haze, respectively. An estimated 926 and 25 per million people cancer cases were attributable to the respiration of the particle-bound and gas phase of 16 PAHs during the haze episode and non-haze, respectively. BaP (60%–80%) and DaA (4%–22%) were the dominant compounds that contributed to the toxicity. In comparison to the previous studies in Thailand, the average $\Sigma$BaP$_{eq}$ and ECR during the non-haze episode in this study was comparable to the study in Tak province in the year 2016 (Janta et al., 2020) but was higher than the other studies during 2010–2013, except in the haze episode in 2010 (Pongpiachan et al., 2015; Wiriya et al., 2013). In this study, however, the $\Sigma$BaP$_{eq}$ and ECR during the haze episode in 2018 was the highest compared to previous years in Thailand. This result indicated currently high health risk to the people in northern Thailand. Compared to other Asian countries, the $\Sigma$BaP$_{eq}$ and ECR in the haze episode was comparable to that in Beijing China during non-source control but lower than that in Xi'an, China (Bandowe et al., 2014; Jia et al., 2011). During the non-haze, the $\Sigma$BaP$_{eq}$ in Thailand was lower than that in Korea, but during the haze episode, it was higher compared to all seasons in Korea (J. Y. Kim et al., 2012).

4. Conclusions

High concentrations of PM$_{2.5}$ and PAHs were observed during the haze episode. Eighty-three percent of the PM$_{2.5}$ measurements in the haze episode exceeded the Thailand national ambient air quality standard. A high cancer case was estimated from this study, with an average value of 926 per million people during the haze episode in upper north Thailand. In most of the provinces, the concentration of PAHs in the urban area was higher than that in the rural area. All 16 PAHs were detected in the study area. Phase partitioning of PAHs depended on the molecular weight. Low molecular weight PAHs were detected only in the gas phase. In contrast, the high molecular weight was detected only in the PM-bound phase. In the haze
episode, mean gas-phase PAHs concentration was 90.5 ng/m³ about 2 times higher than the PM-bound phase (42.7 ng/m³), and the PM-bound PAHs tend to be more absorbed on the fine fraction. The DRs results suggest that PAHs were derived from mixed sources of vehicle exhaust and biomass/coal combustion. Seasonal variation of sources resulting in PAHs in air collected from the upper north Thailand was detected by the application of DRs. The PCA indicated the strongest relation of traffic sources in the non-haze, whereas biomass combustion was the represented source in the haze period.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

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