Characterization of particulate matter (PM$_{1}$ and PM$_{2.5}$) from incense burning activities in temples in Vietnam and Taiwan

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Abstract

Particulate matter (PM) emitted from incense burning is a serious problem because of its effects on human health and the environment, especially on the air quality of Southeast Asia. This study investigated the PM$_1$ and PM$_{2.5}$ concentrations in two temples in Vietnam and Taiwan, focusing on events (i.e., new moon and full moon day) and non-event days using PM sensors. Moreover, PM$_{2.5}$ samples were collected to determine organic carbon (OC) and elemental carbon (EC) concentrations. The PM$_1$ and PM$_{2.5}$ concentrations in Vietnam (22.7±18.7 and 36.5 ± 33.9 µg m$^{-3}$, respectively) were lower than those at the Taiwan temple (74.5±53.4 and 97.0±65.4 µg m$^{-3}$, respectively). The incense burning activity in the Taiwan temple occurred inside the temple while the incense burner at Vietnam’s temple was located outdoors. During the event days, PM$_1$ and PM$_{2.5}$ concentrations were about two times greater than on non-event days, highlighting the impact of incense burning on the PM concentrations. By breaking the study area into control and exposure sites, we found that the people inside the temple experienced 2–5 times higher PM concentrations as compared to those in the ambient air. The PM$_1$/PM$_{2.5}$ ratio was 0.6±0.1 for the Vietnam temple, which was lower than the Taiwan value (0.7±0.1). The OC and EC concentrations in the Taiwan temple were 129.40±97.68 and 1.16±2.31 µg m$^{-3}$, respectively, significantly greater than those found in the Vietnam temple (OC = 27.70±7.66 µg m$^{-3}$, EC = 1.63±0.93 µg m$^{-3}$). Furthermore, the OC/EC ratio in the Vietnam temple (20.24) was similar to those reported from incense and biomass in previous research. The increase in religious activities was the major factor leading to the enhancement of the air pollutant levels surrounding the study areas. This study provides valuable information on PM and carbonaceous aerosols emitted from incense burning in Southeast Asia megacities.

Keywords: Southeast Asia Megacities, Particulate matters, OC-EC, Incense burning, Hi-ASAP.
1 INTRODUCTION

Incense has been used for centuries in religion practice, especially in Asian countries. The ritual of offering incense at temples is a popular custom in many Asian countries, especially those that practice Buddhism and Taoism. Incense burning emits a significant amount of pollutants, mainly particulate matter, influencing the air quality and human health (Bootdee et al., 2016; Lui et al., 2016). Incense burning is still considered to be a common PM$_{2.5}$ emission source in Asian countries (Lung et al., 2022). For example, a study in Thailand suggested that the concentrations of PM$_{2.5}$ measured inside a temple could reach 184 - 625 µg m$^{-3}$ during special occasions (Bootdee et al., 2016). Previous studies have indicated that low quality incense could be the source of the high emission rate of particles in the temple (Zhang et al., 2015). However, Lee and Wang (2004) found that using high quality and environmentally friendly incense did not reduce the pollution emission. A review study by Alfano indicated that incense burning was a major factor influencing indoor PM$_{2.5}$ concentrations (Alfano et al., 2020). A study in Vietnam found a 61.6% elevation of indoor PM$_{2.5}$ concentrations at houses that burned incense compared to those without incense burning (Tran et al., 2021). In Taiwan, it was found that incense burning resulted in 40.3 ± 35.5 µg m$^{-3}$ of PM$_{2.5}$, which was 1.53 ± 1.79 times the concurrent outdoor levels, when the subjects burned incense at houses for 30-60 minutes (Lung et al., 2021). Moreover, a pilot-scale study in France indicated that burning an incense stick emitted a maximum concentration of 25,500 particles cm$^{-3}$, and the indoor PM$_{2.5}$ concentration reached 197 µg m$^{-3}$ (Ji et al., 2010), which was 13 times higher than the guideline from WHO for 24 h (15 µg m$^{-3}$). Along with PM$_{2.5}$, burning incense also emits a large amount of PM$_{1}$, which has an aerodynamic diameter much smaller than PM$_{2.5}$; thus, it can lead to more severe health problems because it reaches deeper into the lung (Chen et al., 2021; Kumar et al., 2014). Even though studying PM$_{1}$ from incense burning is necessary, such studies remain limited worldwide.
On the other hand, the ingredients in worshipping incense include resins, spices, aromatic wood and bark, herbs, flowers, essential oils, and synthetic substitute chemicals used in the perfume industry (Jetter et al., 2002). The high variety of components cause burning incense to emit chemical compounds such as carbonaceous aerosol, carbon monoxide (CO), nitrogen oxides, and inorganic ions (Bootdee et al., 2016; See and Balasubramanian, 2011). These chemical compounds can directly affect human health and cause oxidative DNA damage (Chuang et al., 2013) or cell inflammation (Cohen et al., 2013). Previous research in Singapore found that exposure to incense smoke significantly increased the risk of respiratory tract cancer (Friborg et al., 2008) and cardiovascular mortality (Pan et al., 2014). In a Taiwan study, exposure to incense burning had a significant immediate impact on heart rate variability, much higher than the impact from exposure to cooking activity (Tsou et al., 2021).

Among the pollutants emitted by incense burning are carbonaceous aerosols (i.e., OC and EC), which are high in PM$_{2.5}$ and have significant impacts on health (Wang et al., 2006). OC is carbon found in hundreds of different organic substances such as aliphatic and aromatic compounds, acids, and numerous unidentified compounds (Watson et al., 2001), some of which may be mutagenic or carcinogenic, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs/Fs) (Feng et al., 2006; Li et al., 2008). EC is also a potential transporter of toxic compounds into human and animal respiratory systems (Wang et al., 2006). Therefore, studies to characterize OC and EC are needed.

In Southeast Asia, Vietnam and Taiwan have a long tradition of Buddhism and Taoism, sharing a similar culture of going to the temple and praying with burning incense. According to government reports, the numbers of temples in Vietnam and Taiwan were 18,491 and 12,303, respectively (Taiwan Executive Yuan, 2020; Vietnam Buddhist Sangha, 2020). Worshipping in the temples has been the most popular religious activity in the two countries, since 61.7% of the
Vietnamese (Folk religion and Buddhism) (The Pew Forum, 2012) and 68.1% of the Taiwanese (Taoism and Buddhism) (Taiwan Ministry of the Interior, 2006) practice their belief in the temples. Every year, 3580 tons of incense are burned in Taiwan’s temples (Lin et al., 2008), and the amount in Vietnam could be even higher because of the larger population. Therefore, indoor air pollution in the temple has gained much attention in the two countries. Thanks to the collaboration in the Health Investigation and Air Sensing for Asian Pollution (Hi-ASAP) research initiative (Lung et al. 2022), the research teams in the two countries are equipped with efficient and similar research facilities to conduct this research.

The objectives of this study are (1) Providing information about the characterization of the PM$_1$ and PM$_{2.5}$ from incense burning in Vietnam and Taiwan temples and comparing the difference in PM$_1$ and PM$_{2.5}$ concentrations between event days and non-event days; (2) Determining the PM$_{2.5}$-bound OC-EC to understand the characteristics and identification of carbonaceous aerosol from incense burning at a temple in Vietnam - a country in Southeast Asia; (3) Improving the knowledge about particulate matter emission as well as the composition of carbonaceous aerosols emitted from incense burning in Vietnam and Taiwan, a case study at Asia.

2 METHODS

2.1 Sampling site

This research was conducted at two typical temples in Vietnam and Taiwan. In Vietnam, the temple is in Ho Chi Minh City (HCMC; Fig. 1; 10.78N, 106.74E) and is one of the most famous temples with an area of 6000 m$^2$ and about 400 – 2600 worshippers per day. In Taiwan, we conducted our research at a 250-year-old Taoist temple in the urban area of Taipei. The temple is located at 25.05N, 121.57E in an area of 2000 m$^2$. Ho Chi Minh City and Taipei City are the largest cities in each country, each with a concentration of many temples (1469 and 271 in HCMC and
Taipei, respectively). These two temples were selected because of their popularity; however, the results from this study are not representative of all the temples in the respective countries. The main incense burners in the Vietnam temple are located in the roofless temple yard, while other indoor censers are small and not open for public incense burning. The temple in Taiwan is located fully indoors with no restriction on placing incense in any censer.

Figure 1. The sampling sites in Vietnam (a) and Taiwan (b).

2.2 Sampling strategy

According to the tradition in Southeast Asia, people usually go to the temple on the full moon day (15th) and the new moon day (1st) to pray for good luck. In this study, PM$_1$ and PM$_{2.5}$ concentrations were measured in these two periods. Each monitoring period (either new moon or full moon day) included the events 2 days before and 2 days after the day.
In Vietnam, the study was carried out during 2 periods: lunar 2021, 13-17 March (lunar March 15th, full moon day), and lunar 29 March to 3 April (lunar April 1st, new moon day). The measurement was conducted in the morning (from 7:30 to 11:30) and in the afternoon (from 13:45 to 17:45). The PM low-cost sensors (i.e., ASLUNG-P) provided by Academia Sinica, Taiwan, were employed to monitor the PM$_{1}$ and PM$_{2.5}$ concentrations. The researcher carried the instrument near the chest and covered each area in the temple (A1, A2, A3), called the exposure site (Fig. S1). The total time for one measurement round in the exposure site was about 30 minutes. Simultaneously, for comparison purposes, another ASLUNG-P was set at the entrance to the temple, called the control site. The control site was 50 m away from a three-lane road in front of the temple (Fig. S1). The number of worshippers was counted every 30 minutes. Moreover, PM$_{2.5}$ was also sampled using the SKC Sampler to analyze OC and EC. This device was fixed in the A2 area (Fig. S1), 1 – 1.5 m from the large censer and placed at a height of 1.5 m from the ground.

In Taiwan, the monitoring campaign was carried out during 2 periods: lunar 2021, 29 September to 3 October (lunar October 1st, new moon day), and lunar 13-17 October (lunar October 15th, full moon day). According to the traditional belief, worshipping is preferred in the morning. Therefore, all the monitoring was performed from 8:00-12:00 in the morning. In the control site, one ASLUNG-P sensor was fixed on a shelf at a height of at least 120 cm. This site was located on a pavement 10 m from the entrance and away from a four-lane road running in front of the temple. To sample PM in the exposure site, one ASLUNG-P sensor and a personal environmental monitoring (PEM) system were loaded on a backpack and carried by the researcher. The sampling inlets of all instruments were located above the chest of the researcher to resemble the actual breathing exposure. To simulate the actual worshipping pathway, every hour the researcher followed the worshipping path and spent 2-3 minutes at each censer (within a distance of 2 m) before moving to the next one. In total, the researchers approached 10 censers, which took roughly
40 minutes for each round. After finishing the worshipping path, the researcher returned to the main hall to wait for the next round. In addition to the censers for incense burning, joss paper burners were also located inside the two temples.

### 2.3 Instrumentation

Four ASLUNG-P sensors were used in this study. In Taiwan, the sensors were all calibrated according to a research-grade instrument GRIMM Model 1.109 (GRIMM Aerosol Technik Ainring GmbH & Co, Ainring, German) before going into the field. In Vietnam, the sensors were calibrated with TSI DustTrak (TSI Inc, USA) after DustTrak was calibrated with the gravimetric method. The calibration equation is reported in Table S1. In the Vietnam temple, PM\textsubscript{2.5} samples were collected on pre-treated quartz filters (Advantec, Japan) at a flow rate of 10 L min\textsuperscript{-1} for OC and EC analysis. Prior to sampling, all samplers were calibrated to achieve a recommended flow rate of 10 L min\textsuperscript{-1}. Before use, quartz filters were heated at 400\textdegree C to remove impurities for 8 hours, cooled, stabilized in a plastic Petri dish and placed in a desiccator at 25\textdegree C with an RH of 30-40%. After sampling, the filters were put into a plastic Petri dish, then wrapped with a layer of aluminum foil to avoid photochemical reactions and determine the mass after stabilizing, and stored at -20\textdegree C.

In Taiwan, the PM\textsubscript{2.5} samples were collected onto filters using a personal environmental monitoring (PEM) system. The PEM sampling head was equipped with 17 mm quartz filters. Before sampling, all the quartz filters were treated at 900\textdegree C to avoid contamination. The samples were collected with a BGI-400 pump at the flow rate of 10 L min\textsuperscript{-1} for 4 hours or until the filters were saturated. The filter was then collected and brought back to the laboratory for OC/EC analysis.

### 2.4 Analysis of OC and EC

In Vietnam, a quarter of each sample was analyzed for OC and EC by a model 5L OC/EC Carbon Analyzer (Sunset Inc., USA) that employed thermal/optical transmittance (TOT). The temperature was set up using the NIOSH870 (National Institute of Occupational Safety and Health)
with five OC fractions (OC1, OC2, OC3, OC4 and OC5 at 310, 475, 615, 870 and 550°C, respectively, in a non-oxidizing helium atmosphere) and six EC fractions (EC1, EC2, EC3, EC4, EC5 and EC6 at 550, 625, 700, 775, 850 and 870°C, respectively, in an oxidizing helium atmosphere of 2% O2 and 98% helium). The pyrolysis of OC (OP) was continuously monitored by the reflectance or transmittance of laser signals. OC was operationally defined as OC1 + OC2 + OC3 + OC4 + OC5 + POC, and EC was defined as EC1 + EC2 + EC3 + EC5 + EC6 – OP.

In Taiwan, the quartz filters were not weighted. Particulate OC and EC were measured on the model 4 OC/EC Semi-Continuous Carbon Analyzer (Sunset Laboratory Inc., USA), following the IMPROVE A (Interagency Monitoring of Protected Visual Environments) thermal/optical reflectance protocol (Chow et al., 2007). The temperature procedure of the IMPROVE A protocol was 140, 280, 480, and 580°C for OC1, OC2, OC3, and OC4 fractions, respectively, and 580, 740, and 840°C for EC1, EC2, and EC3 fractions, respectively. The filters were analyzed in an oxygen-free environment of pure helium, and the contents of the carbonaceous components in the quartz filter were measured.

3 RESULTS AND DISCUSSION

3.1 General characteristics of mass concentrations of PM1 and PM2.5 at the exposure sites

In the Vietnam temple, the average concentrations of PM1 and PM2.5 at the exposure site were 22.7 ± 18.7 and 36.5 ± 33.9 µg m⁻³, respectively, in which, the average PM values in period 1 and period 2 were not significantly different (Wilcoxon test, p-value < 0.05). In the Taiwan temple, the average concentrations of PM1 and PM2.5 at the exposure site were 74.5 ± 53.37 and 97.0 ± 65.4 µg m⁻³, respectively. The concentrations of PM1 and PM2.5 from incense-burning activities at the Vietnam temple were about 3.3 times (for PM1) and 2.6 times (for PM2.5) lower than at the Taiwan temple. The summary data are illustrated in Table S2. This difference could be due to the design of
each temple. The temple in Vietnam was located on a large open space. All the large censers were placed outdoors so the emitted air pollution could be easily dispersed to the ambient air. On the other hand, the temple in Taiwan was a closed indoor temple where all the burning activities were conducted indoors. Therefore, the indoor air pollution measured in the Taiwan temple was higher than that of Vietnam temple. The PM$_{2.5}$ concentrations in the Vietnam and Taiwan temples exceeded the standards of the US EPA (35 µg m$^{-3}$) and the WHO 24-hour guideline (15 µg m$^{-3}$). Moreover, the PM$_{2.5}$ concentration in the Vietnam temple met the National Ambient Air Quality Standards (NAAQSs) of Vietnam (50 µg m$^{-3}$). For Taiwan, however, the PM$_{2.5}$ concentration exceeded the NAAQSs from Taiwan (35 µg m$^{-3}$). For comparison, PM$_{2.5}$ levels in Vietnam were lower than those of a shrine in Thailand (50 µg m$^{-3}$) (Bootdee et al., 2016) and 10 temples in India (658.3 µg m$^{-3}$) (Bhadauria et al., 2022) while the PM$_{2.5}$ value in the Taiwan temple was greater than that in the Thailand temple. The design of the temple could have contributed to the PM$_{2.5}$ concentration. Outdoor incense burning in Vietnam’s temple (this study) was found to have a lower PM$_{2.5}$ concentration than the open ceiling incense-burning room in Thailand’s temple (Bootdee et al., 2016), followed by the closed ceiling incense burning in Taiwan’s temple (this study). Moreover, the instrument and sampling design might have caused the difference between this study and the abovementioned Thailand and India studies. In those studies, PM$_{2.5}$ was collected using a filter-based sampling method in which the samplers were in a fixed position in the temple, whereas in our study, PM$_{2.5}$ was measured using a real-time monitoring system that was carried by researcher around the temple. Therefore, our study might have better represented the PM$_{2.5}$ concentrations in different locations in the temples. Because there are no standards for PM$_1$ (Li et al., 2019), this study compared concentrations of PM$_1$ with other studies. PM$_1$ values at Jokhang Temple in China using real-time personal aerosol monitors (AM510 SidePak™) were 435.0 ± 309.5 µg m$^{-3}$ (Cui et al., 2018), 4 – 20 times higher than those found in the two temples in this
Another result in Taiwan showed that PM$_1$ values were slightly higher than the result in Vietnam, averaging about 33.7 µg m$^{-3}$, which were measured by GRIMM (Lung et al., 2014). Nevertheless, PM$_1$ in the Taiwan temple in this study was greater than in the previous study in 2014.

The PM$_1$ and PM$_{2.5}$ concentrations were significantly different at both events and non-events in Vietnam (Wilcoxon test, p-value < 0.05). The PM$_1$ and PM$_{2.5}$ values ranged from 7.8 – 298.1 µg m$^{-3}$ (average 37.5 ± 30.8 µg m$^{-3}$) and 17.2 – 717.7 µg m$^{-3}$ (average 58.1 ± 61.8 µg m$^{-3}$) at the events. The PM$_1$ and PM$_{2.5}$ concentrations during events were about 80 – 90% greater than during pre- and post-events (Fig. 2), and a similar pattern was observed in Taiwan. Generally, the trendlines of PM$_1$ and PM$_{2.5}$ suddenly increased when the researchers stood near the censers, and they fluctuated strongly on event days. The PM concentrations were associated with the number of worshippers (r=0.65, p-value < 0.05), which could be related to the number of incense sticks (Bootdee et al., 2016). During the event, approximately 2000 worshippers were at the temple, which was 2 – 4 times higher than the number on non-event days (Table S3). Similarly, during these two days in Taiwan, the number of pilgrims significantly increased, leading to higher incense-burning activities (Table S3). Consequently, the concentrations of particulate matter almost doubled during event days compared to non-event days. Elevations of particulate matter during event days were associated with the increasing number of people visiting the temples during those days. The correlation coefficient between the number of visiting people and the concentrations of particulate matter was significant for both PM$_1$ (r=0.47, p-value < 0.001) and PM$_{2.5}$ (r=0.44, p-value < 0.001). For PM$_1$, the concentration on event days was 120.3 ± 48.8 µg m$^{-3}$, which was 1.9 times higher than that on non-event days (62.8 ± 47.9 µg m$^{-3}$). Similarly, the concentration of PM$_{2.5}$ during event days (149.9 ± 59.6 µg m$^{-3}$) was 1.80 times higher than that on non-event days (83.4 ± 59.6 µg m$^{-3}$). It was also found that particulate matter (PM$_{2.5}$) was higher during event days compared to non-event days, such as in a study in Taichung, Taiwan, where PM$_{2.5}$ concentrations
were 81.2 and 59.5 µg m\(^{-3}\) during event days and non-event days, respectively (Fang et al., 2002), or in Chiang Mai where the average 8-hour PM\(_{2.5}\) concentrations were 184 ± 85 µg m\(^{-3}\) during event days and 100 ± 35 µg m\(^{-3}\) during non-event days (Bootdee et al., 2016).
Figure 2. Time series of PM$_1$, PM$_{2.5}$ at control sites during two events in a Vietnam temple (a, b) and a Taiwan temple (c, d).
Figure 3. A shorter time frame when the PM sensor was moved closer to the censer.

Additionally, to gain insight into the contribution of incense burning to urban air, this study compared PM$_1$ and PM$_{2.5}$ values between the exposure site and the control site. The PM concentrations at the exposure site in the Vietnam temple were 22.7 ± 18.7 µg m$^{-3}$ for PM$_1$ and 36.5 ± 33.9 µg m$^{-3}$ for PM$_{2.5}$ higher than those at the control site (12.6 ± 6.1 µg m$^{-3}$ for PM$_1$ and 23.7 ± 8.9 µg m$^{-3}$ for PM$_{2.5}$). Our results were similar to a study in Hong Kong, in which the indoor/outdoor ratios of PM$_{2.5}$ were 1.63 – 2.30 times higher (Wang et al., 2007). Moreover, the PM ratios between exposure and control sites were elevated during the events as compared to non-events (Fig. 4 and Fig. 5). The ratio of PM slightly increased +7.1% (PM$_1$), +11.0% (PM$_{2.5}$) on pre-15$^{th}$ days and decreased strongly -29.6% (PM$_1$), -28.8% (PM$_{2.5}$) on post-15$^{th}$ days. However, the increase in the PM ratio between pre-1$^{st}$ and post-1$^{st}$ days was remarkable, with values of +31.2% (PM$_1$), +41.7% (PM$_{2.5}$) and -22.7% (PM$_1$), -29% (PM$_{2.5}$), respectively. Similarly, in Taiwan, compared to the exposure site, the concentrations at the control site were significantly (Wilcoxon test, p-value < 0.001) at 13.1 ± 6.84 and 17.68 ± 10.24 µg m$^{-3}$ for PM$_1$ and PM$_{2.5}$, respectively. This result implied that those entering the temple were exposed to concentrations of particulate matter five times higher than those exposed to ambient air. Moreover, for non-event days, we found that post-event days in Taiwan and pre-15$^{th}$ days in Vietnam showed higher particulate matter than other non-event days because those were weekend days. People tend to go to the temple when they have the day off rather than on weekdays. So, at the two temples on weekends, PM concentrations were higher than on the weekdays.
Figure 4. Ratio of PM$_{1}$ (a) and PM$_{2.5}$ (b) at the exposure site and control site in the Vietnam temple.

Figure 5. Ratio of PM$_{1}$ (a) and PM$_{2.5}$ (b) at the exposure site and control site in the Taiwan temple.

Worshippers usually assemble at A1 to praise good fortune or burn incense instead of gathering at A2 and A3 because of the large space at A1 in the Vietnam temple (Fig.3). Therefore, PM values at A1 were significantly different from the remaining areas (Wilcoxon test, p-value < 0.05) (Fig. 6). For A2 and A3, which are inside the temple, the air pollution hardly dispersed, resulting in PM concentrations that were almost the same. Moreover, to simulate the real exposure situation of people inside the Taiwan temple, in addition to monitoring the general environment inside the temple, the researcher also approached the censer. When the researchers walked around the temples, the concentrations of PM$_{1}$ and PM$_{2.5}$ were 55.8 ± 54.3 and 72.1 ± 66.3 µg m$^{-3}$, respectively. This concentration was significantly elevated when the researcher approached the worshipping distance (<2 m from the censer). Close to the censer, the average concentrations of
PM$_1$ and PM$_{2.5}$ reached 91.1 ± 46.61 and 119.1 ± 55.9 µg m$^{-3}$, respectively (Fig. 7). Moreover, we found that when the researcher walked around the temple, the concentrations of particulate matter fluctuated greatly (high standard deviation). This fluctuation indicated that even when the people were not at the worshipping distance, they could still be exposed to a high concentration, mostly owing to walking close to people holding incense. In Vietnam, a high peak of PM concentration was also observed (Fig. 3) when the researcher approached the incense burner. This result implied that when the worshippers stayed close to the censers, they might be exposed to much higher PM concentrations.

Figure 6. PM at three areas in the Vietnam temple.
Figure 7. PM concentration for two cases: worship distance (<2 m near the censer) and around the Taiwan temple (>2 m away from worshipper to the censer).

To investigate the emission characteristics of the particulate matter from incense burning, the mass concentration ratio of PM$_1$/PM$_{2.5}$ should be considered (Cui et al., 2018). Therefore, we further analyzed the PM$_1$/PM$_{2.5}$ ratios in the two temples. Fig. 8 shows that the ratios of PM$_1$/PM$_{2.5}$ at two sites (exposure and control sites) in the Vietnam temple had similar trends during the sampling time. Both mean ratios of PM$_1$/PM$_{2.5}$ in period 1 and period 2 were 0.6 ± 0.1 (0.3 – 0.8) at the exposure site, which were lower than those found at temples in China (0.9) (Cui et al., 2018). For other sources, the ratios of PM$_1$/PM$_{2.5}$ from public traffic, biomass burning, and coal combustion were 0.7, 0.6, and 0.8, respectively (Gerber et al., 2014; Wang et al., 2020; Khan et al., 2021). The main ingredients of the incense stick produced in Vietnam are from plants (*Litsea glutinosa*, *Lindera myrrha*, gumtree (eucalyptus), *Aquilaria crassna*, and cinnamon powder) (Chinh et al., 2020), so the PM$_1$/PM$_{2.5}$ ratio from incense burning and biomass burning can be similar. The mean ratio of PM$_1$/PM$_{2.5}$ at the exposure site was quite high, whereas this ratio at the control site was only 0.5 ± 0.2 (0.4 – 0.7) (p-value < 0.05). Sources with high PM$_1$/PM$_{2.5}$ values were focused on because the health impacts are associated with fine particles, as shown in epidemiological studies.
Moreover, PM emitted from incense burning, which has a high PM$_1$/PM$_{2.5}$ ratio, should be considered further. The health risk assessment of worshippers at temples in Vietnam is more vital. In Taiwan, we found that the PM$_1$/PM$_{2.5}$ ratios found at both the exposure site and control site were similar and stable at 0.73 and 0.76, respectively. This similarity indicated that the particulate matter at the control site and exposure site shared common origin. Therefore, the particle concentrations outside the temple could be influenced by the incense-burning activities inside the temple. Moreover, during the event day, the elevations in particulate matter were observed not only indoors but also at the outdoor sampling site. Since there was no change in the meteorological conditions and traffic conditions between the event and non-event days, the elevation in particulate matter concentrations at the outdoor sampling site could only be explained by the dispersion of particles from the indoor temple. This result suggested that people living in the vicinity of the temple could be exposed to air pollution from the temple’s activities even without going into the temple. Comparably, the ratio of PM$_1$/PM$_{2.5}$ at the exposure site in the Vietnam case study was lower than in Taiwan. The basic ingredients of incense sticks in Taiwan can be different from those in Vietnam. Moreover, the combustion process could influence the PM$_1$/PM$_{2.5}$ ratio (Wang et al., 2020), so this might be one reason for the difference between the PM$_1$/PM$_{2.5}$ ratios in the two temples. A higher proportion of PM$_1$ compared to PM$_{2.5}$ means that the burning process of Taiwan’s incense was more complete than that of Vietnam’s incense. In addition, at the control site in the Vietnam temple the PM$_1$/PM$_{2.5}$ ratio was lower than at the exposure site, while the PM$_1$/PM$_{2.5}$ ratio at the control site in the Taiwan temple was approximately the same as the reported ratio at the exposure site. This indicated that ambient air in the vicinity of the Taiwan temple may have been affected by the incense-burning activities in the temple. In both Vietnam and Taiwan, the outdoor sampling sites were all located near the temple gate (10 m); however, the Vietnam temple has a long distance from the main censer to the gate (50 m) and much more open space. Therefore,
the direct impact of incense burning on the outdoor sampling site in Vietnam’s temple was not as significant as that on Taiwan’s temple. Because of the great distance from the incense-burning site, the PM concentration at the control site in Vietnam’s temple could be affected by other sources such as traffic, which was next to the sampling station. Although there was an increase in air pollution at the control site in Vietnam during event days, this could have been due to the effect of vehicles going to the temples rather than to incense burning itself. In contrast, for the case study in Taiwan, the PM sources from the control site and the exposure site were the same. The activity of burning incense in the Taiwan temple may have affected the concentration of PM in the ambient air.

![Figure 8](image.png)

**Figure 8.** PM$_1$/PM$_{2.5}$ ratio at exposure and control sites in Vietnam (left) and Taiwan (right).

### 3.2 OC and EC

Inside the temple, the average concentrations of OC and EC were 27.70 ± 7.66 and 1.63 ± 0.93 µg m$^{-3}$, respectively, for Vietnam and 129.4 ± 97.68 and 1.16 ± 2.31 µg m$^{-3}$, respectively, for Taiwan. The OC concentration in the Vietnam temple was 4.7 times lower than that in Taiwan. However, the EC concentration in Vietnam was 1.4 times higher than Taiwan’s EC concentration. In the Vietnam temple, the mass percentages of OC and EC in PM$_{2.5}$ were quite high (Fig. 9), averaging 42.4 ± 11.68% for OC and 2.4 ± 1.2% for EC. Compared with previous global studies on the carbon composition of PM$_{2.5}$ emission from incense burning, the contribution percentages
of OC and EC in the Vietnam temple were lower than in these studies (Wang et al., 2007; See and Balasubramanian, 2011).

**Figure 9.** Mass percent concentration of OC and EC to total PM$_{2.5}$ mass in the Vietnam temple.

In this study, OC and EC concentrations in the two periods reached the maximum value on both event days, including the 15th (the full moon day) and the 1st (the new moon day). Between the two days of intense incense-burning activity, the new moon day had significantly higher OC and EC concentrations compared to the full moon day (Fig. 10). This finding was similar to a previous study monitoring the concentration of pollutant emissions from the incense burning on different days at another temple in Vietnam, indicating that the air condition during the new moon day was usually worse than full moon day (Thuy et al., 2021). According to traditional belief, new moon worshipping should be conducted on the first day of the month, and full moon worshipping should be conducted 1-2 days before or after the full moon. Therefore, worshipping activities can be more concentrated during the new moon day than during the full moon day, which in turn emits higher pollution concentrations.
Figure 10. Evolution of OC and EC concentrations at the Vietnam temple during both sampling periods.

The OC/EC ratio of each carbonaceous emission was specific to each source. Therefore, the OC/EC ratio was used as an identification feature for carbon emissions from different sources in previous studies (Schauer et al., 2001; Thuy et al., 2018; Wang et al., 2015; Zhang et al., 2007). The predominance of OC over EC was also observed in previous Hong Kong temple atmospheric measurements, where the OC/EC ratio reached 18 (Wang et al., 2007). In this study, the average OC/EC ratio in the Vietnam temple was 20.24, similar to the OC/EC ratios from burning traditional incense (Wang et al., 2006) and the OC/EC ratio from wood burning (Schauer et al., 2001). This similarity seems to be because the ingredients and materials for making incense are mostly derived from wood. However, in the Taiwan temple, because of a very low EC concentration, the OC/EC ratio was very high (a hundred times). The difference in the OC/EC ratio between the Vietnam and Taiwan temples might be due to the type of incense used, incense burned at a Taiwan temple emits more OC, which leads to a high OC/EC ratio. Moreover, the OC/EC ratios on the two event days were significantly lower than on the days before and after the event. This can be explained by the
lower rate of increase in OC compared with that in EC on the 1\textsuperscript{st} and 15\textsuperscript{th} (Fig. 10), resulting in a marked decrease in the OC/EC ratio on these days. Overall, carbonaceous aerosol at temples tends to increase sharply on major event days, significantly influenced by Buddhist and Taoist customs.

**Figure 11.** Average mass concentrations of 12 carbon fractions in PM\textsubscript{2.5} samples in Vietnam.

Along with the OC/EC ratio, the carbon fraction was used to identify different carbon emission sources (Qi et al., 2018; Wang et al., 2019; Xu et al., 2015). In the Vietnam temple, analysis of the carbon fractions of PM\textsubscript{2.5} samples indicated that OC\textsubscript{1} to OC\textsubscript{4}, OP, EC\textsubscript{4}, EC\textsubscript{5} were fractions with a high mass concentration (Fig. 11). Up to now, there has been almost no research on carbon fractions to identify the source of carbon emissions from incense burning. This study can be considered an important contribution to determining the predominant carbon fraction from incense burning in Vietnam. From there, it might also be an important reference for further studies on OC and EC emissions from incense burning in Vietnam in particular and in Asia in general.

This research found that incense-burning activities in both Vietnam and Taiwan could generate high concentrations of particulate matter and carbonaceous aerosols. Because of the large distance from the incense burner to the gate at Vietnam’s temple, the aerosol was dispersed before reaching the outside area. However, the Taiwan temple was located alongside a residential building,
exposing people living in the surrounding areas to higher particulate matter concentrations, especially during event days. Therefore, to protect the health of the temple workers, worshippers, and people living around the temple, the incense-burning activities should be further restricted through limiting the amount of burned incense or improving air pollution dispersion.

4 CONCLUSION

This study contributed to our understanding of particulate matter emissions while also providing preliminary information on the composition of carbonaceous aerosols emitted by incense burning in Vietnam and Taiwan, a case study in Asia. The PM$_1$ and PM$_{2.5}$ concentrations in the Vietnam temple were about 3.3 times (for PM$_1$) and 2.6 times (for PM$_{2.5}$) lower than the Taiwan temple. In the two temples, the PM concentrations were associated with the number of worshippers ($r > 0.4$, p-value < 0.05). It increased the PM on the event days. Furthermore, if worshippers stand closer to censers, they might be exposed to a higher PM concentration. The concentration in the Vietnam temple was 4.7 times lower than the average OC concentration and 1.4 times higher than the EC concentration in the Taiwan temple. The average OC/EC ratio in the Vietnam temple was 20.24, while the ratio in the Taiwan temple was many times higher. Overall, carbonaceous aerosol levels in temples tend to rise sharply on major event days, owing to Buddhist and Taoist customs. The OC and EC concentrations increased dramatically on event days, but the OC/EC ratio was lower than on the days before and after the event.

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**DISCLAIMER**

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