RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2006.32.039

*ScienceAsia* 32 (2006): **39-46**

# Concentrations and Elemental Analysis of Airborne Particulate Matter in Chiang Mai, Thailand

**Nakorn Tippayawong* and Aleck Lee**

Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai 50200, Thailand.

* Corresponding author, E-mail: nakorn@dome.eng.cmu.ac.th

*Received 16 Feb 2005*
*Accepted 9 Sep 2005*

**ABSTRACT:** Air pollution, especially airborne particulate matter, is becoming a major problem in Chiang Mai. The present study reports findings on total suspended particulate matter (TSP) loading as well as its spatial and daily variation in Chiang Mai ambient air. Limited elemental analysis of airborne particulate matter was also performed. Samples were collected at four different sites, representative of urban, industrial, residential and rural areas during day time between October 2003 and April 2004. TSP mass concentrations ranged from 50 – 370 $\mu g/m^3$, with average concentration of 149 $\mu g/m^3$. A similar order of magnitude was observed for mass concentrations at different sites. The maximum monthly averaged TSP concentration observed at a busy commercial site was about 2-fold higher than the maximum TSP found at a suburban residential site. A daily variation of TSP concentrations was found to be significant, with occasional peaks well above Thailand's national ambient air quality standards (NAAQS) for 24 h TSP of 330 $\mu g/m^3$, observed during the morning rush hours. Elemental analysis results showed that the likely TSP sources were crustal matter from soil and road dust (Fe, Ca, Al and K) as well as vehicular and industrial emissions (Pb, Zn and Cr).

**KEYWORDS:** Aerosol, TSP, Mass concentration, Elemental composition.

## INTRODUCTION

In newly industrialized countries, emission controls are usually not keeping pace with economic development, energy consumption and urban population growth. As a result, urban air pollution tends to rise. Atmospheric aerosols are one of the main air pollutants in urban areas. The potential adverse impacts of particulate air pollution on human health and the environment have been a major concern for the public and the government. A substantial number of epidemiological studies e.g. COMEAP[1], Pope *et al*[2], HEI[3], have demonstrated a strong correlation between levels of particulate matter in regions and cities and a number of adverse health effects. Airborne particulate matter is a complex mixture of liquid and solid particles that exist in a dynamic equilibrium with the surrounding vapor phase. It has a wide range of physical and chemical properties, most of which undergo constant transformation within the atmosphere. The particles may originate from natural or anthropogenic sources and may be either primary or secondary emissions. The extent of the contribution to the total aerosol from variety of different sources varies locally, diurnally and seasonally, and is affected by weather conditions.

In view of air quality assessment, among the most important parameters of particulate matter is the mass concentration. Air quality standards are mass-based and have a size-related aspect to measurement, concentrating on $PM_{10}$ (which is particulate matter with aerodynamic diameter less than 10 μm and able to penetrate deep into the human respiratory system). Current ambient levels of particulate matter in Thailand are on average lower than the air quality standards, as reported by the Thailand's Pollution Control Department, however, occasional episodes of locally high concentration of $PM_{10}$ particularly in highly polluted areas may occur in cities like Bangkok. In addition, even at a concentration level below these limits, a small percentage of people may experience adverse health effects because of individual susceptibility, pre-existing medical conditions and/or hypersensitivity (allergy). Particulate air pollution was one of pollutants demonstrated to have serious short and long-term health effects, even at current low ambient levels. Health effects, which arise from exposure to concentrated particulate matter, may range from irritation and annoyance, loss of organ function, to morbidity and mortality. Some of these effects can be acute and reversible, while others develop gradually into irreversible chronic conditions. The respiratory system and eyes are the main organs affected. Children, elderly people and people with pre-existing respiratory or cardio-vascular diseases are especially vulnerable

to fine particulate matter. Evidence exists to suggest that short-term changes in mortality, hospital admissions, lung function and symptoms are associated with ambient PM levels, and that long-term prevalence of symptoms and mortality from respiratory diseases is associated with ambient aerosol levels.[4] A study in Bangkok by Ostro *et al*[5] estimated that a 10-$\mu$g/m$^3$ change in daily $PM_{10}$ is associated with a 1-2 % increase in natural mortality, a 1-2 % increase in cardiovascular mortality, and a 3-6 % increase in respiratory mortality.

Chiang Mai is one of the major cities in Thailand. The city accommodates government offices, shopping complexes, medical, agricultural and educational institutions, industrial units and residential areas. Growing urbanization, traffic volume, commercial and industrial activities have resulted in increased concentrations of airborne particulate matter and other gaseous pollutants. The city is situated down near Ping river valley and surrounded by Suthep mountain ranges. Generally, the wind is not strong, so the smog and haze are concentrated above the city. Thus the air quality in the critical areas and other less polluted areas in Chiang Mai remains bad and often gets even worse. It is worrisome that particulate air pollution problems in Chiang Mai have emerged to be equally serious, like those in urban Bangkok and its suburb. It is essential that air pollution studies and research may not only focus on Bangkok and its perimeter but also be extended to other problematic regions of the country, including Chiang Mai.

There exists a general lack of data regarding the absolute ambient levels of TSP and $PM_{10}$ across Chiang Mai and how these levels vary spatially and temporally. It is therefore of great importance to quantify the levels and study the patterns of airborne particulate matter in the city. Mass measurements are not well documented. There are few data investigating other physical parameters of particulate that are now becoming of interest (size and number), and even less data exist regarding the chemical composition of ambient particulate aerosol. This study is an attempt to gain better knowledge of air pollution levels and their compositions so that meaningful data are available to the decision makers and measures can be implemented to control and reduce air pollution for better air quality in the future.

## Experimental

### Site Description – Chiang Mai, Thailand

Thailand is located in the middle of Southeast Asia, neighbored by Myanmar, Laos, Cambodia and Malaysia. Chiang Mai (18°78'N, 98°59'E, 314 m above sea level), the chosen study area, is the second largest city in Thailand. It is situated 700 km from Bangkok in the upper north region of the country. Chiang Mai is situated

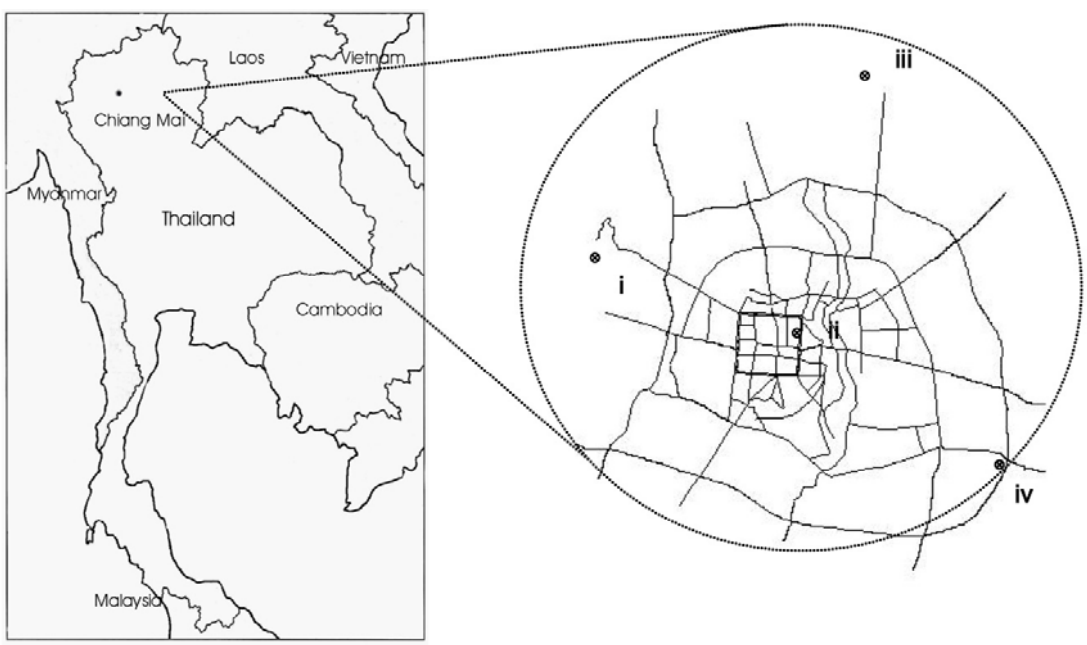


**Fig 1.** Locations of air sampling stations in Chiang Mai, Thailand, (i) Chiang Mai University, (ii) Ta Pae, (iii) Maejo and (iv) Sankampaeng.

in the Ping River valley near the foothills of Suthep Mountains. It is surrounded by medium height mountain ranges in the northern, eastern and western parts. The northwestern Suthep Range essentially blocks the air movement from the Northwesterly and Southeasterly winds during cool and rainy seasons respectively, to wash out the air pollution. The city is a major center of economic growth as well as a regional trade, public administration, education, communication and transportation hub. Government offices, shopping complexes, medical, agricultural and educational institutions, industrial units, commercial and residential areas are close and sometimes mixed together. The city has a population of about 400,000 with about 3 million visitors a year. As a result of growing population and economic prowess of Chiang Mai, the number of vehicles on roadways jumped from around 400,000 in 1993 to nearly 550,000 in 2000. The study areas cover the Municipality of Chiang Mai and adjoining areas with average population density of about 4,300 people per $km^2$. The area and location are depicted in Figure 1. Sampling locations were chosen to reflect different influences from industrial, commercial and residential parts of the city. The four sampling sites are Ta Pae – a busy commercial area with heavy traffic; Sankampaeng – a small industrial and residential area with medium traffic; Maejo – a small commercial and residential area with low traffic; Chiang Mai University – a residential area with low traffic.

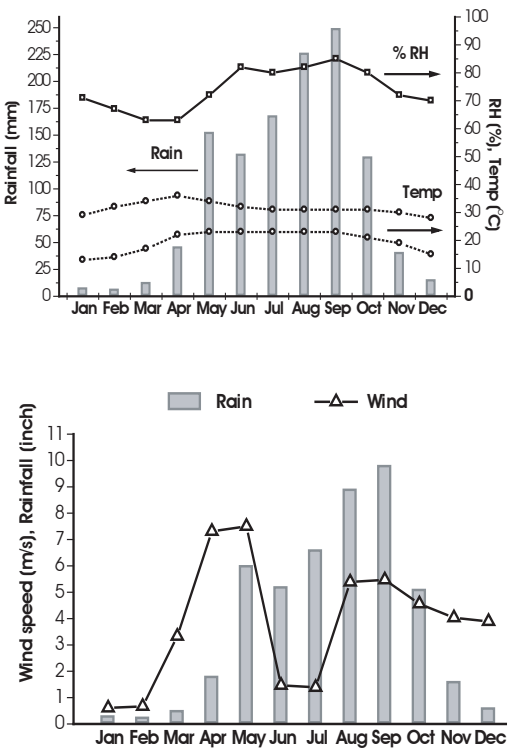


**Fig 2.** Meteorological conditions in Chiang Mai, Thailand.

## Meteorology of Chiang Mai, Thailand

The climate of Thailand is subtropical, characterized by high temperature and humidity. Meteorologically, the year of Thailand can be divided into three seasons. The cool and dry season runs from December to March. The summer (April – July) is normally hot and humid. During the rainy season (August – November) the downpours can be extremely heavy, but generally only last for an hour or so. Monthly average ambient conditions in Chiang Mai are shown in Figure 2. The usual temperature variation was 10 to 20 °C during one month. For daily temperature fluctuation, moderately higher temperatures were observed in the afternoon. The average wind speed was about 3.0 m/s.

## Sampling

The total suspended particulate matter samples were collected by a low volume sampler over a ten-hour (0800 – 1800) period as a daytime average at each sampling site. New collection was performed everyday for four consecutive days of the same week in the months of October 2003, December 2003, January 2004 and April 2004. The samples were equipped with stainless steel filter holder (Gelman no. 2220) on a glass fiber filter (Whatman EPM2000, 47 mm diameter) applying an average sampled air volume of 35 $m^3$. Sampling was performed at the 2nd floor of a building on a balcony about 4 m above ground for all four sites. Field blanks were determined for each sampling site and considered for the calculation procedures. After the end of each sampling, the filters loaded with PM sample were carefully removed from the filter holder, stored in clean Whatman Petri dishes, and kept under controlled humidity and temperatures during sampling period to minimize losses due to volatilization and evaporation. A total of 64 samples were collected, although several samples were contaminated by rains and had to be discarded. Only 56 sampled filters were available and kept between four to eight weeks prior to elemental analysis. The filters were later transported to Department of Industrial Chemistry, Chiang Mai University for analysis. For some cases in which PM loading was low, two or more samples were analyzed and treated as one sample.

Along side the air filtration setup, a Casella Microdust Pro aerosol mass monitor was used to measure airborne particulate mass concentration. The instrument was set to operate between 0800 – 1800 of each day at each sampling site. New measurements were performed everyday for four consecutive days of the same week in the months of October 2003,

December 2003, January 2004 and April 2004. A total of 16 days worth of data for each site was obtained. The instrument measures particulate concentrations using a near forward angle light scattering technique. Infrared light of 880 nm wavelength is projected through a measurement chamber where contact with particles causes the light to scatter. The light within the chamber is blocked from reaching the receiver by a light stop. When a particle passes through the chamber, the beam is scattered forward within a narrow angle around the light stop and onto the receiver, thus registering the presence of particles in the air stream being monitored. The amount of scatter is proportional to the mass concentration and is measured by the photodetector. By using a narrow angle of scatter (12-20°) the majority of scattered light is in the diffracted and refracted components, which minimizes the uncertainty associated with particle color, shape, and refractive index. The device used has a lower measurement limit down to 1$\mu$g/m$^3$. It was calibrated according to manufacturer specifications. The unit is a small portable particle measurement device with self-contained power supply. The LCD display allows viewing of time series mass concentration in real time. The measurement volume is typically 3.0 ml. It comes with a probe that attaches to the inlet nozzle with a short piece of tubing. Measurement was performed at 30 minute interval and the data was automatically logged within the instrument memory and can be easily transferred to a computer through a data acquisition and process control software.

### Elemental Analysis

The concentrations of limited choices of elements were determined by atomic absorption spectroscopy (AAS)[6,7] for Al, Fe, Pb, Zn, Cd, Cr and Ni and by flame photometer[8] for Ca, Na and K, respectively. Each solid sample (filter paper loaded with PM sample) was directly heated in a crucible until all carbonaceous matter was removed. The ash was then allowed to cool down, and later transferred to a flask. The ash was treated with 10 ml of concentrated $HNO_3$ and 30 ml of concentrated HCl. All the reagents used were of analytical grade. The mixture was digested at 60°C for at least 2-3 hours or until the mixture appeared to have no residue. Digested liquid samples were filtered and reconstituted to 100 ml by adding solution of 1.0% $HNO_3$ in deionized double distilled water. High purity stock solutions of 1,000 ppm (mg/dm$^3$) of different metals were used as standards. The atomic absorption determinations were measured by the Perkin-Elmer Corporation AA analyst 100 instrument and the flame emission spectroscopy were performed using the Sherwood Flame Photometer model 410 and all data were sampled and processed automatically via a personal computer using AA Win/Lab software. The spectrometer was operated in the absorption mode (absorbance readings), using at least three standard solutions for calibration. For each element determination, the recommended wavelengths and burner position were set. Flame conditions (in terms of $C_2H_2$, air, $N_2O$) were adjusted against a standard solution to obtain optimum output for the concentration range of the element considered. Deionized water was atomized after each reading of standard or sample. Similar procedure was performed for the photometer. The calibration curves were prepared by plotting the absorbance versus concentration for each standard. From calibration graphs, a metal concentration of a sample was calculated by comparing the absorbance of the sample solution with that of the standard metal solution in fixed concentration, purchased from Reagocon, Ireland and Sherwood Scientific, UK.

## Results and Discussion

### TSP Concentrations

Figure 3 shows ranges of monthly 10 h TSP levels as well as each respective averaged value measured at the four locations from October 2003 to April 2004. All sampling locations exhibited relatively high TSP concentrations, ranging from 50 to 370 $\mu$g/m$^3$ with an average concentration of 149 $\mu$g/m$^3$. The 10 h average value was well below Thailand NAAQS, 24 h TSP standard of 330 $\mu$g/m$^3$ and also below the US EPA TSP 24 h standard of 260 $\mu$g/m$^3$ which was used, prior to the adoption of $PM_{10}$ standard in 1987. However, there were a few findings in January 2004 reported to exceed 24 h TSP standard of Thailand. It should be noted that the TSP concentrations from this study were 10 h daytime averaged. The values should generally be higher than 24 h averaged values when both day and night times are taken into account. However, the values were markedly lower than the values (310-886 $\mu$g/m$^3$) reported for roadside TSP in Chiang Mai by Matsushita

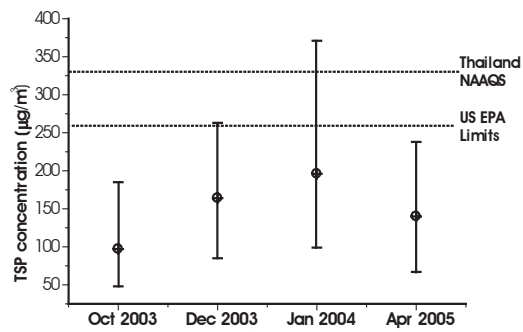


**Fig 3.** Average monthly TSP concentrations in Chiang Mai ambient air.

*et al*.[9] In comparison with some large cities located in Asia, the particulate matter concentration measured in Chiang Mai is relatively high. For example, average TSP concentrations in Seoul, Hong Kong, Bangkok, Jarkarta, Ho Chi Minh City, and Karachi were 153, 78, 127, 211, 74 and 668 $\mu$g/m$^3$, respectively.[10,11,12] It should be pointed out here that measurements were performed around the months of cool and dry season (December and January) when highest particulate matter concentrations occurred, consistent with those reported by Vinitketkumnuen *et al*.[13] Lower TSP loading seen on October and April were due in part to washout by rain during the sampling period.

Figure 4 shows variation of TSP levels during a typical day measured at all the locations for the months of December and April. Spatial variation is a good indicator for identifying the importance of local emission sources. Ta Pae, the representative of busy commercial site appeared to have the highest TSP loading, as anticipated. Mass loadings in Sankampaeng and Chiang Mai University were high (mixed areas) and relatively low in Maejo (residential area). The pattern was similar for both months. Even though comparison of urban TSP level is not quite straight forward because the concentrations can be site specific, a similar trend was observed for different sampling sites in Chiang Mai. This may be expected because the furthest distance between any two sites is only about 15 km. All sampling locations exhibited fluctuations of TSP concentrations with time. The temporal variations of concentration pattern for each site were also similar. The variations are mainly due to weather and meteorological conditions such as temperature, relative humidity and wind speed which affect the dispersion of airborne particulate matter. Additionally, changes in source emission strength with time also have impacts on these variations. High level of TSP in Chiang Mai may be caused by dust re-suspension, open biomass burning and vehicular emissions. Other sources may come from industrial processes or construction activities. For rural and residential sites, the TSP level was relatively constant throughout the day, while commercial and industrial areas witnessed an increase in concentration during morning rush hour, a gradual reduction thereafter. Marginal increases in TSP concentration were observed again during lunch break. The levels of TSP did not appear to decline towards the evening, instead, a rise in concentration was evident. The temporal variation was particularly clear for Ta Pae site. The fluctuation observed was in accord with traffic pattern in the city with existing congestion peaks in the morning, the afternoon and the late afternoon.[14] After a close inspection of the typical daily CO and $NO_2$ patterns[15] (shown in Figure 5) obtained from a monitoring station which is located close to Ta Pae, it was found that the peaks of the gaseous emissions occur around 0800, 1730 and again around 2000. Gas concentrations around lunchtime were relatively stable. The infrared

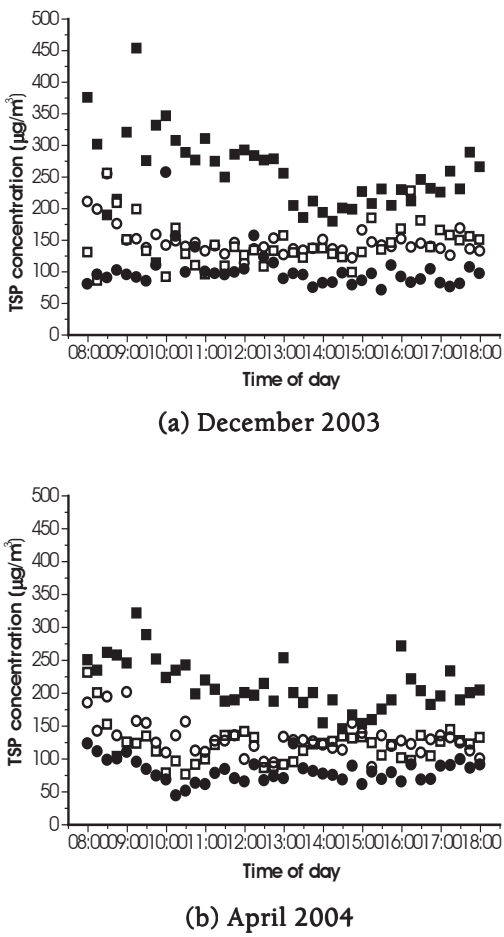


**Fig 4.** Typical daytime variation of TSP concentrations in Chiang Mai ambient air measured by infrared method at: Ta Pae (■), Sankampaeng (○), Maejo (●), and Chiang Mai University (□).

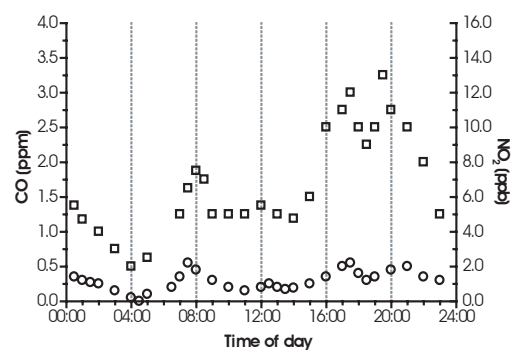


**Fig 5.** Typical daily variation of CO ( ○ ) and $NO_2$ ( □ ) concentrations obtained from a Pollution Control Department monitoring station at Chiang Mai city center.

**Table 1.** Elemental concentration and average PM concentration (in$\mu g/m^3$) in the Chiang Mai air and comparison with other Asian cities.

| Element this study | Chiang Mai Chueintaet *al.*[16] | Bangkok Hien *et al.*[11] | Ho Chi Minh City Salamet *al.*[7] | Dhaka Sohrabpour *et al.*[18] | Tehran Qin *et al.*[19] | Hong Kong |
|---|---|---|---|---|---|---|
| Al | 2.37 | 2.05 | 2.53 | - | 3.95 | 0.275 |
| Ca | 2.50 | 2.69 | 2.82 | 6.83 | 7.61 | 0.731 |
| K | 2.72 | 0.800 | 0.789 | 1.55 | 2.4 | 0.459 |
| Na | 8.10 | 0.531 | 0.770 | 1.27 | 1.74 | 1.50 |
| V | - | 0.012 | 0.007 | - | 0.014 | 0.011 |
| Cr | 0.321 | - | 0.009 | - | 0.056 | - |
| Cd | 0.013 | - | - | 0.003 | - | 0.001 |
| Zn | 0.508 | 0.129 | 0.203 | 0.801 | 0.288 | 0.102 |
| Fe | 4.51 | 1.06 | 2.90 | 24.8 | 2.72 | - |
| Ni | 0.025 | - | - | - | 0.046 | 0.004 |
| Pb | 0.147 | - | 0.146 | 0.279 | 1.04 | 0.066 |
| Br | - | 0.026 | 0.009 | - | 0.42 | 0.015 |
| PM | 149[a] | 49.9[b] | 73.6[a] | 516[c] | - | 55.3[d] |

[a] measured as total suspended particulate matter.
[b] measured as fine and coarse particulate matter, the value shown was sum of the two components.
[c] measured as elemental carbon, organic materials, soluble ions, trace and soil elements, the value shown was sum of the total components.
[d] measured as respirable suspended particulate matter.

measurements of TSP appeared to capture the morning rush hours but not the high traffic in the late evening. Several peaks were also observed during the day due to traffic emissions or nearby activities such as open burning and floor sweeping.

## Elemental Composition

Selected metals were determined from TSP collected from the four sites in Chiang Mai. Table 1 shows and compares the average results of this work with those for the cities of Bangkok, Ho Chi Minh City, Dhaka, Tehran and Hong Kong. It should be noted that particulate matter from Bangkok and Hong Kong were not measured as TSP, unlike other cities in Table 1. The general levels of polluting elements in Chiang Mai were comparable to those measured in other cities. High concentration of the potassium was observed. It was thought to be coming from biomass burning.[16] This was consistent with reports of forest fires and open burning of vegetation in Chiang Mai during cool and dry season. However, inspection of the K/Fe ratio suggested that the majority of K may have been from crustal matter. K in aerosol from biomass smoke was therefore estimated, similar to Chan *et al* 's work.[17] The potassium smoke indicator was found to give a positive but not significant value ($0.014\ \mu g/m^3$). Soil and road dust and construction industry related (Al, Ca, Fe) elements[11] appeared to have a high concentration pattern throughout the period. They were dominant elements in TSP. Concentrations of the elements Pb and Zn seemed relatively high, comparing with cities in nearby region (Bangkok and Ho Chi Minh City). Since the phase out of leaded gasoline in 1995, it was unlikely that Pb in TSP was coming from the traffic. It may likely be from the suspended road dust or local industries emitting Pb. As the source of Pb cannot be identified conclusively, the issue should be further investigated. High loading of Na element was not expected. It seemed unlikely that marine aerosol via a continental air mass movement contributed to Na in inland Chiang Mai TSP. A study in Bangkok[16], nearer to coastal site, showed a smaller average value. It was suggested that contamination from diluting water can add significant amount of Na even with care. Furthermore, the flame photometry method used in this study may have tendency to yield high Na with large uncertainty. Nonetheless, it was recommended that further study on this matter should be carried out. Other elements did not seem to display a specific concentration pattern.

## Health Implications

It was evident that Chiang Mai air has high TSP loadings. TSP contains all sizes of aerosol, including particulate matter with aerodynamic diameter $< 10\ \mu m$ ($PM_{10}$) and $< 2.5\ \mu m$ ($PM_{2.5}$) which are inhalable. Recent epidemiological and toxicological studies[3] and health impact assessment[5,20] have been conducted on these particles. Although the regulatory compliance metric was changed to $PM_{10}$ and $PM_{2.5}$, much of data used in setting the standard were based on TSP measurements. Many studies in which TSP or $PM_{10}$ were measured were analyzed with derived $PM_{2.5}$ values based on assumed relationships between TSP, $PM_{10}$ and $PM_{2.5}$.[21] It is therefore interesting to deduce $PM_{10}$ and $PM_{2.5}$ concentrations in Chiang Mai air from TSP data. The ratios of $PM_{10}$/TSP and $PM_{2.5}$/TSP were derived from

the US EPA standards, 150 $\mu$g/m$^3$ for $PM_{10}$, 65 $\mu$g/m$^3$ for $PM_{2.5}$, and 260 $\mu$g/m$^3$ for TSP, to be 0.58 and 0.25, respectively. Martuzzi *et al*[20] used the ratio of 0.55 to estimate $PM_{10}$ from TSP in their Italian study. The calculation shows that the ranges of $PM_{10}$ and $PM_{2.5}$ were estimated to be 30-215 and 9-93 $\mu$g/m$^3$, respectively. The level of airborne particulate matter deduced from this study was above the baseline level at which deaths, hospital admission and respiratory conditions were predicted to be in excess. The baseline levels used by Martuzzi *et al*[20] were 30 and 40 $\mu$g/m$^3$ for $PM_{10}$. It was clear that particulate matter levels in Chiang Mai atmosphere were high, serious health problems may be expected to occur. Our preliminary findings stress upon a need for a detailed study on the TSP, especially, $PM_{10}$ and $PM_{2.5}$ in Chiang Mai air. The move from TSP to $PM_{10}$ and $PM_{2.5}$ is necessary not only from public health considerations, but also for enhancing the contrast between manmade and natural crustal sources.

## Conclusions

Investigation of airborne particulate matter concentration in Chiang Mai has been performed. This study has clearly shown that Chiang Mai has high TSP loading in its ambient air, in the range of 50-370 $\mu$g/m$^3$, with an average concentration of 149 $\mu$g/m$^3$. Variation of TSP concentrations was also significant with occasional peaks well above the Thailand NAAQS (330 $\mu$g/m$^3$) and the US EPA limits (260 $\mu$g/m$^3$), especially in a busy commercial area. Limited elemental composition analysis showed that TSP seemed to come from re-suspended soil and road dust, local industrial and construction sites as well as biomass burning. The results obtained from this study may be useful for assisting with strategic planning and regulation. An effective control strategy should be developed and implementation should be carried out by local and state authorities to avoid particulate air pollution becoming a major problem in Chiang Mai.

## Acknowledgements

Financial support of this research project from the Thailand Research Fund is gratefully acknowledged. The authors would also like to express thank to Dr S. Chaiklangmuang for her technical assistance and discussions.

## References

1 COMEAP (1998) *Quantification of the effects of air pollution on health in the United Kingdom*, Committee on Medical Effects of Air Pollution, Department of Health, The Stationery Office, London.
2 Pope CA, Dockery DW and Schwartz J (1995) Review of epidemiological evidence of health effects of particulate air pollution. *Inhol Toxicol* **7**, 1-18.
3 Health Effects Institute. (2002) Understanding the health effects of components of the particulate matter mix: progress and next steps. *HEI Perspectives*, available online at <http://www.healtheffects.org> access on April 2002
4 Harrison R (1996) *Pollution: causes, effects and control*, Royal Society of Chemistry, Cambridge.
5 Ostro B, Chestnut L, Vichitvadakan N and Laixuthai A (1999) The impact of particulate matter on daily mortality in Bangkok, Thailand. *J Air & Waste Manage Assoc* **49**, 100-7.
6 Perkin-Elmer Corporation (1996) Atomic absorption spectroscopy analytical method manual. Perkin-Elmer Corporation, USA.
7 Salam A, Bauer H, Kassin K, Ullah SM and Puxbaum H (2003) Aerosol chemical characteristics of a mega-city in Southeast Asia (Dhaka-Bangladesh). *Atmos Environ* **37**, 2517-28.
8 Sherwood Scientific (1992) Guideline to flame photometric analysis. Sherwood Scientific, UK.
9 Matsushita H, Takahashi Y, Amagai T and Koottatep S (1998) Polynuclear aromatic hydrocarbons in the roadside atmosphere in Chiang Mai, Thailand. *J Environ Chem* **8**, 63-70.
10 Panther BC, Hooper MA and Tapper NJ (1999) A comparison of air particulate matter and associated polycyclic aromatic hydrocarbons in some tropical and temperate urban environments. *Atmos Environ* **33**, 4087-99.
11 Hien PD, Binh NT, Truong Y, Ngo NT and Sieu LN (2001) Comparative receptor modeling study of TSP, $PM_2$, and $PM_{2-10}$ in Ho Chi Minh City. *Atmos Environ* **35**, 2669-78.
12 Parekh PP, Khwaja HA, Khan AR, Naqvi RR, Malik A, Shah SA, Khan K and Hussain G (2001) Ambient air quality of two metropolitan cities of Pakistan and its health implications. *Atmos Environ* **35**, 5971-8.
13 Vinitketkumnuen U, Kalayanamitra K, Chewonarin T and Kamens R (2002) Particulate matter, PM 10 & PM 2.5 levels, and airborne mutagenicity in Chiang Mai, Thailand. *Mutat Res* **519**, 121-31.
14 Kuranami C, Mastuoka S, Chua MY, Nakagawa Y, Arimoto K, Yamaguchi Y, Rose C and Ogita S (2001) The study on improvement of road traffic environment in Chiang Mai city in the Kingdom of Thailand. Japan International Cooperation Agency, interrim report, October 2001,
15 Pollution Control Department (2005) Airviro indico presentation for Yubharaj station, available online at <http://bangkok.pcd.go.th/cgi-bin/priv-36T/wwwindico_36T> access on June 2005
16 Chueinta W, Hopke PK and Paatero P (2000) Investigation of sources of atmospheric aerosol at urban and suburban residential areas in Thailand by positive matrix factorization. *Atmos Environ* **34**, 3319-29.
17 Chan, YC, Simpson RW, McTainsh GH, Vowles PD, Cohen DD and Bailey GM (1997) Characterisation of chemical species in PM2.5 and PM10 aerosols in Brisbane, Australia. *Atmos Environ* **31**, 3773-85.
18 Sohrabpour M, Mirzaee H, Rostami S and Athari M (1999) Elemental concentration of the suspended particulate matter in the air of Tehran. *Environ Intl* **25**, 75-81.
19 Qin Y, Chan CK and Chan LY (1997) Characteristics of chemical compositions of atmospheric aerosol in Hong Kong: spatial and seasonal distributions. *Sci Total Environ* **206**, 25-37.

20 Martuzzi M, Galassi C, Ostro B, Forastiere F and Bertollini R (2002) Health impact assessment of air pollution in the eight major Italian cities. European Centre for Environment and Health, WHO Europe report no. EURO/02/5040650, available online at <http://www.euro.who.int/healthimpact> access on June 2005
21 McClellan RO (2002) Setting ambient air quality standards for particulate matter. *Toxicology* **181-2**, 329-47.