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Full Length Research Paper

Reducing emissions of air pollutants from incense burning with the addition of nanoscale calcium carbonate

Chi-Ru Yang [1]*, Yen-Shun Peng [2] and Yih-Feng Chang[3] and Ying-I Tsai[1]

[1]Department of Environmental Engineering and Science, Chia-Nan University of Pharmacy and Science, Tainan 71710, Taiwan.
[2]Department of Environmental Resources Management, Chia-Nan University of Pharmacy and Science, Tainan 71710, Taiwan.
[3]Department of Tourism Management, Chia-Nan University of Pharmacy and Science, Tainan 71710, Taiwan.

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Many studies have investigated the particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs) emissions of burning incense on the quality of surrounding air. However, the reduction of PM and PAHs from burning incense has received little attention. In the present study, two types of incense were made in the laboratory. Five to thirty percent of nanoscale calcium carbonate (nano-$CaCO_3$) was added to Hsing Shan and Lao Shan wood flours, which are popular incense materials. It was found that the addition of 10% nano-$CaCO_3$ reduced PM by 7.30 mg/g and reduced particle-phase PAHs by 1.03 µg/g and benzo[a]pyrene equivalent by 0.15 µg/g. In addition, considering the total consumption of incense, we added 10% nano-$CaCO_3$ in incense powder. Then, it can reduce PM by 73.0 tons, particle-phase PAHs by 10.3 kg, and benzo[a]pyrene equivalent by 1.5 kg in Taiwan per year. The findings of this study may serve as a guide to producing safer and less-polluting incense.

Key words: Incense, calcium carbonate, particulate matter, polycyclic aromatic hydrocarbons, benzo[a]pyrene equivalent.

INTRODUCTION

Worshiping ancestors and gods by burning incense sticks has been one of the important traditions in many Asia regions. There are 6.1 million families in Taiwan (Taiwan MOI, 2010), with 45% burning incense twice per day (Lung et al., 2007). Cancer, asthma, dermatitis, and genotoxic effects are related to exposure to incense smoke (Dawod and Hussain, 1995; Jetter et al., 2003; Yang et al., 1997). Chiang et al. (2009) indicated that the incremental lifetime cancer risk is greater than the acceptable level of 10^{-6} for temple workers exposed through the inhalation route.

Burning incense in an enclosed room results in a suspended particle concentration of 390 to 730 µg/m^3, which is 4 to 7 times higher than the indoor air particulate standard of the Taiwan EPA (100 µg/m^3) (Kao and Lung, 2000). In our previous study, it was found that the PM emission factor from nine types of incense ranged from 15 to 47 mg/g with an average of 33 mg/g, which is higher than that for cigarettes (10 mg/g) (Löfroth et al., 1991; Yang et al., 2007). In addition, we found that the shorter the combustion duration of a stick, the lower the total suspended particulate emission. For given incense weight burned, the greater the emission of ash is, the lower the emission of suspended particulate matter (Lin et al., 2007).

In our previous study, gas-phase PAHs (G-PAHs) and particle-phase PAHs (P-PAHs) emission factors ranged from 10 to 29 and 4.5 to 6.9 µg/g, respectively. However, the particle-phase benzo[a]pyrene equivalent (BaP_{eq}) emission factor was found to be consistently more than 40-fold higher than that of the corresponding gas-phase

*Corresponding author. E-mail: cryang@mail.chna.edu.tw. Tel: +886 6 2664911 ext 6414. Fax: +886 6 2669090.

BaP_{eq}. These results clearly suggest that in terms of carcinogenic potency, the P-PAHs emission is more important than G-PAH emission for incense burning (Yang et al., 2007).

Cheng et al. (1995) found that the count median diameter and mass median aerodynamic diameter (MMAD) of smoke aerosol from incense burning in an enclosed chamber were 0.13 and 0.28 μm, respectively. In our previous study, it was found that most of the suspended particulates in the incense smoke were smaller than 5.6 μm, with 95% of them smaller than 1.0 μm, and that the average MMAD of the smoke aerosol was 0.262 μm (Yang et al., 2007). Notably, particulate matter less than 2.5 μm in diameter ($PM_{2.5}$) accounts for most PM generated by burning incense. Fine particles are more likely to harm the respiratory system as they can easily be inhaled and deposited in the respiratory tract and alveolar region (Harrison et al., 2000; USEPA, 2002; Voutsa and Samara, 2002). The efficiency of particle deposition in the respiratory tract is a function of the particle size (Pope et al., 1995). Unfortunately, the reduction of PAHs and PM from burning incense has received little attention.

It is well known that nano-$CaCO_3$, which has high specific surface and thermal insulation. Yang et al. (2007) indicated the zinc-hydroxystannate coating was applied to magnesium hydroxide and nano-$CaCO_3$., and the coating process made nano-$CaCO_3$ become the most effective additive at lowering polyvinyl-chloride (PVC) flammability and smoke output. Dynamic mechanical thermal analysis showed that the addition of nano-$CaCO_3$ led to an increase in storage modulus and glass transition temperature for both PVC and PVC/Blendex blend (Chen et al., 2004). We investigated nine types of incense and found that incense with higher $CaCO_3$ content had lower PM and PAH emissions (Yang et al., 2006). Therefore, the incense used in the present study was made in our laboratory. In order to control the variations of incense characteristics, we added nano-$CaCO_3$ and identified the reduction of PM and PAH emissions in burning incense. The findings of this study may serve as a guide to producing safer and less-polluting incense.

MATERIALS AND METHODS

Manufacture of test incense

The raw materials of incense used in this study include bamboo and powder (adhesive, wood flour and nano-$CaCO_3$). Most of the bamboo was Makino bamboo (Phyllostachys makinoi Hay). The natural adhesive was made of the bark of Machilus kusanoi Hay (a species of Lauraceae), which becomes sticky when mixed with water. The wood flour was made of pulverized powder of various woods. Incense is named after its wooden materials; popular incense includes Hsing Shan and Lao Shan.

Two types of commonly used wood flour were selected for Hsing Shan incense and Lao Shan incense. Hsing Shan and Lao Shan are usually categorized as sandalwood incense. They are mainly made from the powder of Hsing Shan wood and Lao Shan wood, respectively. Hsing Shan wood is usually younger and cheaper than Lao Shan wood. Chinese herbal fragrance is usually added for the purpose of lowering and cost and increasing the fragrance. Although little Chinese herbal fragrance is usually added (<10%), some are still made from the pure powder of Hsing Shan wood.

In this study, the incense was partially handmade to reduce experimental error and to keep the process consistent. We choose the most popular incense quantity in Taiwan as experimental materials, which length and weight of the bamboo stick were 39.5 cm and 0.55 g. Then, wood flour and adhesive were sieved using a No. 50 screen mesh (0.300 mm). The bamboo stick, wood flour, and adhesive were equilibrated with 50% humidity for 24 h before the manufacture of test incense. Each batch of incense used 100 g of incense. Users prefer incense with a long burning time. We pre-tested the nano-$CaCO_3$ additive in powder and ensured incense burning time at above 60 min. The percentages by weight of nano-$CaCO_3$ in the powder were 5, 10, 20 and 30%. The powder was then mixed with 100 g of deionized water. Aquiferous powder was pressed onto the bamboo stick with a hydraulic press machine to make semifinished incense.

The length of the compressed sticky powder part (combustion part) was 28.0 cm. The combustion part of the bamboo was about 0.39 g. The semifinished incense was then dried in air for two days. The finished samples were conditioned in a carriage at 25°C under a relative humidity of 50% for 24 h before being weighed. Various types of incense with various amounts of additive were made. The weights of the samples were 1.01±0.02 g. The weights of chosen incense samples were exactly 1.00 g in order to control the variation from the physical characteristics of incense. The detailed compositions of the test incense with various amounts of nano-$CaCO_3$ additive are listed in Table 1. Each incense stick combustion part was 0.84 g, including 0.45 g of powder and 0.39 g of bamboo. For nano-$CaCO_3$ concentrations of 5.0, 10.0, 20.0 and 30.0%, the proportions of nano-$CaCO_3$ in the combustion part were 2.68, 5.36, 10.7, and 16.1%, respectively.

Sampling program

A schematic diagram of the sampling apparatus and configuration is shown in Figure 1 (Tsai et al., 2010). Three lab-made sticks of the same type were burned simultaneously during each run. The sticks were ignited with a propane flame which was immediately extinguished to produce smoldering sticks that were inserted into a preweighted drilled metallic plate inside the chamber of the sampling apparatus, a glass tube. Before each run, the glass tube was purged with air that was first filtered through a high-efficiency particulate air (HEPA) filter.

Total particulate matter was collected on a quartz filter (102 mmΦ, Pall) by drawing air out of the glass tube at 30.0 L/min using a modified mid-volume air sampler fastened to the top of the tube. The air flow was monitored every third run using a panel mounted flow meter calibrated with an infrared soap bubble calibrator (Gilibrator-2, Gilian Instrument Corp.). Finally, the outlet air was pumped out of the laboratory. A panel-mounted flow meter was installed in front of a 187-W (1/4-hp) air pump. Our experience has demonstrated that PM is released long after the incense burning appears complete. Hence, to ensure complete collection of PM in each run, the pump was operated for four minutes after the combustion appeared complete. The temperature was between 20 and 40°C during the sampling. We set up replicated tests for 10 types of incense and each of them was performed six times.

Each quartz filter was cleaned by extraction with a mixed solvent (1:1 n-hexane and dichloromethane) for 24 h in a Soxhlet extractor and allowed to equilibrate in a dry box at 25°C and under 50% humidity for at least 24 h. The quartz filter samples were gathered and temporarily stored in a dry and dark carriage at 25°C under a relative humidity of 50% for 24 h before being weighed.

Table 1. Composition of test incense for various amounts of nano-$CaCO_3$ additive.

Test incense a	Nano-$CaCO^3$ in powder (%)	Powder (g)			Bamboo (g) [b]
		Nano-$CaCO^3$ additive	Wood flour	Adhesive	
NC00	0	0	0.36	0.09	0.55
NC05	5.0	0.0225	0.4275	0.09	0.55
NC10	10.0	0.045	0.405	0.09	0.55
NC20	20.0	0.09	0.36	0.09	0.55
NC30 c	30.0	0.135	0.315	0.09	0.55

a: The weight of one stick of all types of test incense was 1.00 g (0.45 g powder and 0.55 g bamboo stick). b: The weight of each stick bamboo burned was 0.39 g. c: NC30: Thirty percentages by weight of nano-CaCO3 in the incense powder.

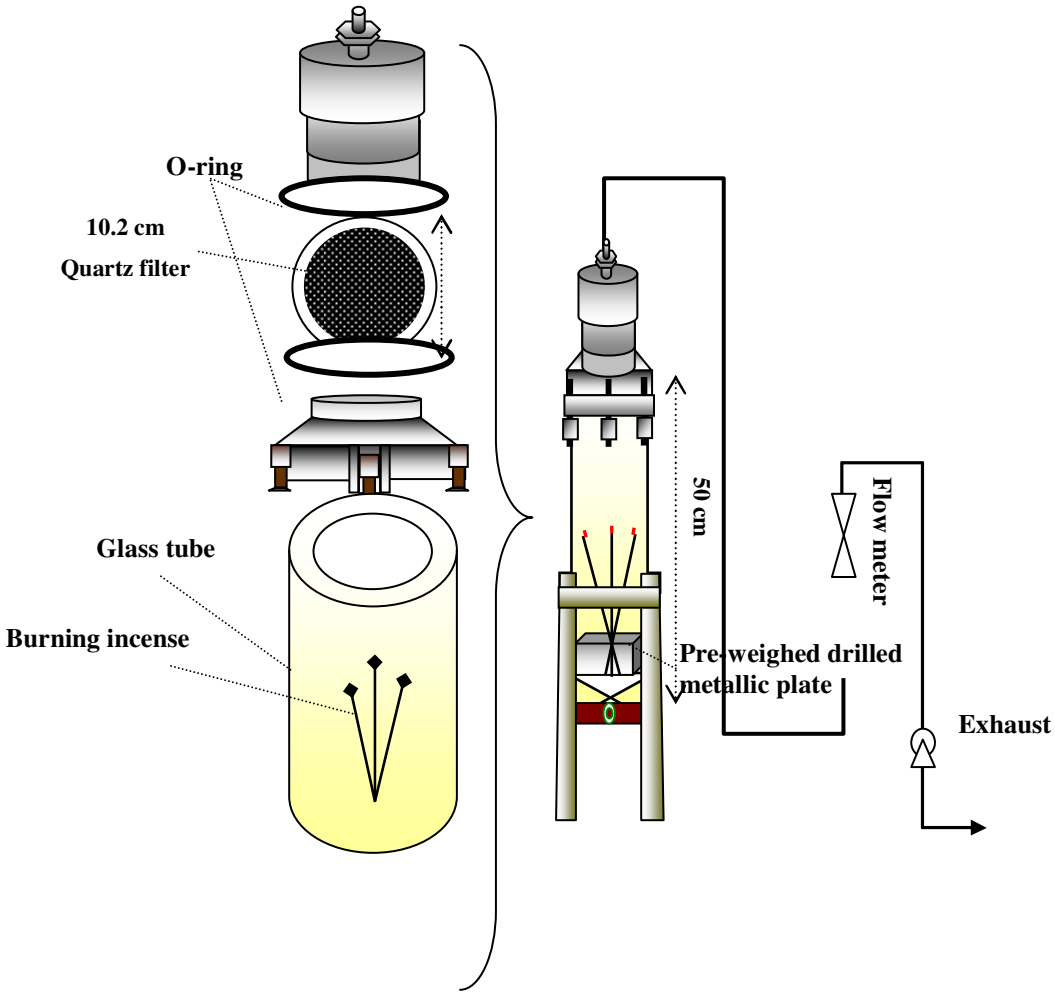

Figure 1. Diagram of incense burning simulation with emitted particulate matter sampling apparatus.

Analyses of PAHs

After final weighing, all filters were separately placed in appropriate Soxhlet extractors and extracted with 600 ml of a dichloromethane/n-hexane mixture (v/v = 1:1) for 24 h. The extract was then concentrated under ultra-pure nitrogen, cleaned, and re-concentrated to exactly 1.0 ml. All extracts were analyzed with a gas chromatograph/mass selective detector (GC/MSD) (GC-6890N with MSD-5973, Agilent Technologies, USA) with a J&W Ultra2 capillary column (50 m × 0.314 mm × 0.17 μm). A computer-controlled automatic sampler (Model 3365, Hewlett Packard, USA) was used in conjunction with the GC/MSD system. All injections were splitless with an injection volume of 1 μl. The injector and the detector temperatures were 300 and 325°C, respectively. The temperature program included an immediate fast initial increase from 50 to 100°C at 20°C/min, followed by a milder

Table 2. Burning time and burning rate of test incense for various amounts of nano-$CaCO_3$ additive.

Test incense	Nano-$CaCO_3$ content of combustion part[a] (%)	Burning time (min)		Burning rate (mg/min)	
		Hsing Shan	Lao Shan	Hsing Shan	Lao Shan
NC00	0	96±1	89±4	26±0	28±1
NC05	2.68	76±2	77±1	32±1	31±1
NC10	5.36	69±1	70±2	36±1	36±2
NC20	10.7	52±2	50±0	49±2	50±1
NC30	16.1	42±1	43±2	61±1	59±3

[a]: Only 0.39 g bamboo was burned, implying that 0.16 g bamboo was left after combustion. N = 6 replicates for each type of incense.

increase from 100 to 290°C at 3°C/min, and finally a hold at 290°C for 20 min. The concentrations of the following PAHs were determined: naphthalene (Nap) for 2-ring; acenaphthylene (AcPy), acenaphthene (Acp), fluorene (Flu), phenanthrene (PA), and anthracene (Ant) for 3-ring; fluoranthene (FL), pyrene (Pyr), benzo[*a*]anthracene (BaA), and chrysene (CHR) for 4-ring; benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo(*a*)pyrene (B*a*P), dibenzo[*a,h*]anthracene (DBA) for 5-ring; and indeno[1,2,3,-*cd*]pyrene (IND), benzo[*ghi*]perylene (Bghip) for 6-ring.

The GC/MSD was calibrated with a diluted standard solution of 16 PAH compounds (PAH mixture-610 M from Supelco). The standard solution concentrations were 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5 and 10 µg/ml. PAH recovery efficiencies were determined by processing a solution containing known PAH concentrations through the same experimental procedure used for the samples. The recovery efficiencies of PAHs varied from 69.1 (Nap) to 98.3 (BaA), with an average of 87.6%. Analysis of serial dilutions of PAH standards showed that the limit of detection of the GC/MSD was between 0.071 and 0.936 ng/ml for individual PAH compounds. Ten consecutive injections of a PAH 610-M standard yielded an average relative standard deviation (RSD) of the GC integration area of 3.0%, with a range of 0.8 to 5.1%. The blank tests for PAHs were accomplished using the same procedure as that used for the recovery-efficiency tests without adding the known standard solution before extraction. Analyses of the blank quartz filter revealed no significant contamination (GC/MSD integrated area < detection limit).

Data analysis

The 16 individual PAHs were divided according to their molecular weight into three categories: Low molecular weight (LM-PAHs containing two- and three-ringed PAHs); middle molecular weight (MM-PAHs containing four-ringed PAHs); and high molecular weight (HM-PAHs containing five- and six-ringed PAHs). The total PAH concentration was the sum of the concentrations for the 16 PAH compounds in each collected sample. Moreover, considering that several PAH compounds are known human carcinogens, the carcinogenic potencies of PAH emissions from each emission source were also determined. In principle, the carcinogenic potency of a given PAH compound is assessed on the basis of its BaPeq. The calculation of the BaPeq concentration for a given PAH compound is determined by its toxic equivalent factor (TEF), which represents the relative carcinogenic potency of the given PAH compound, using benzo[a]pyrene as a reference compound to adjust its original concentration. This study applied the TEFs completed by Nisbet and LaGoy (1992) to assess the carcinogenic potency of total PAHs (that is, total BaPeq) using the sum of the BaPeq concentrations estimated for each PAH compound with a TEF in the total PAHs.

RESULTS AND DISCUSSION

Burning time and burning rate of test incense

Users prefer incense with a long burning time; the higher the burning rate of the incense, the shorter the burning time. The effect of nano-$CaCO_3$ additive on the burning time and burning rate of the test incense, Hsing Shan incense and Lao Shan incense is shown in Table 2. It was found that the burning times of original (NC00) Hsing Shan incense and Lao Shan incense were 96±1 and 89±2 min, respectively. For Hsing Shan incense, the mean reductions of burning time for NC05, NC10, NC20, and NC30 nano-$CaCO_3$ additives were 21, 28, 46 and 56, respectively. For Lao Shan incense, the mean reductions were 13, 21, 44 and 52%, respectively. The mean reductions of burning time were 17, 25, 45 and 54%, respectively, for NC05, NC10, NC20, and NC30. These results indicate that the addition of nano-$CaCO_3$ significantly reduces the burning time. For the burning rate, results similar to those obtained in our previous study, which investigated nine types of incense and found that incense with higher nano-$CaCO_3$ content had higher burning rates, were obtained (Yang et al., 2006). In this study, we controlled the process variations and added accurate amounts of nano-$CaCO_3$ to help verify the reduction of burning time. The results can be applied to the commercial production of incense.

PM emission factor

The PM emission factor results are shown in Figure 2. It was found that the PM emission factor values of original (NC00) Hsing Shan incense and Lao Shan incense were 39.2±0.7 and 37.1±1.3 mg/g, respectively. For Hsing Shan incense, the mean PM reductions for NC05, NC10, NC20, and NC30 were 7.7, 21, 38 and 56%, respectively. For Lao Shan incense, the mean reductions were 14, 27, 43 and 59%, respectively.

The correlations of the PM emission factor and the nano-$CaCO_3$ in powder with regression analysis (r^2 = 0.99, p<0.01 for Hsing Shan; r^2 = 0.98, p<0.01 for Lao Shan) were strongly negative. These results indicate that the reduction of PM emissions increases with increasing

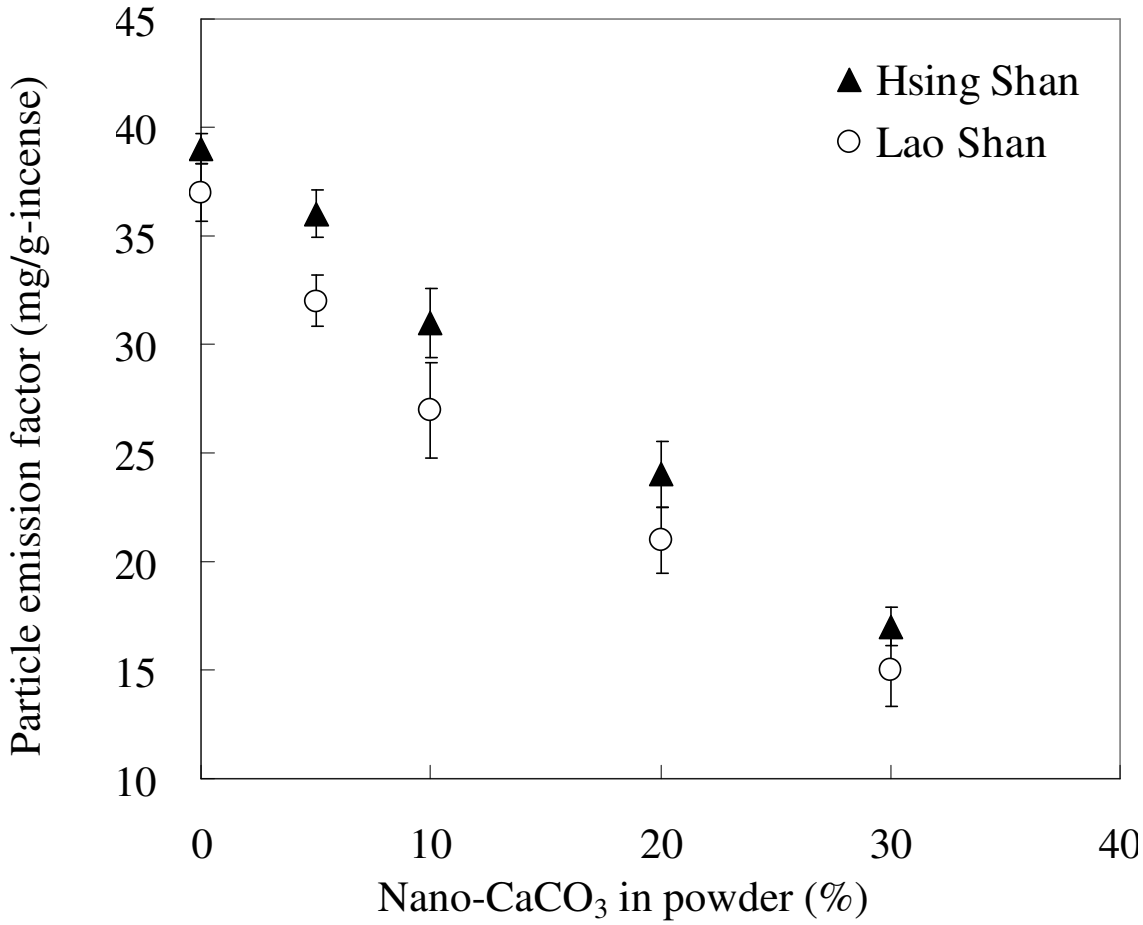

Figure 2. PM emission factor of test incense for various amounts of nano-CaCO3 additive (each error value equals one standard deviation).

amount of nano-$CaCO_3$ additive. Moreover, the nano-$CaCO_3$ content was 2.68, 5.36, 10.7 and 16.1% in the burning part (Table 2), respectively, for NC05, NC10, NC20, and NC30, which are lower than the mean PM reductions for the two types of test incense (11, 24, 41 and 58%, respectively). These results may be attributed to nano-$CaCO_3$, which may trap the heat energy generated at the burning tip during combustion. Moreover, nano-$CaCO_3$ has heat resistance, and therefore prevents air convection and avoided lowering temperature during incense combustion, increasing the burning rate.

P-PAHs emission factors and profiles

The emission factor results of P-PAHs and total BaP_{eq} are shown in Figure 3 and Table 4. It was found that the P-PAH emission factors for original (NC00) Hsing Shan incense and Lao Shan incense were 8.4±0.5 and 7.6±0.5 μg/g, respectively. For Hsing Shan incense, the mean P-PAH reductions for NC05, NC10, NC20, and NC30 were 8, 17, 22 and 41%, respectively. For Lao Shan incense, the mean reductions were 9, 18, 31 and 38%, respectively. The correlations of the P-PAHs emission factor and the nano-$CaCO_3$ in powder with regression analysis (r^2 = 0.97, p<0.01 for Hsing Shan; r^2 = 0.97, p<0.01 for Lao Shan) were strongly negative.

The total BaP_{eq} emission factor values for original Hsing Shan incense and Lao Shan incense were 1.36 and 1.33 μg/g, respectively. For Hsing Shan incense, the mean total BaP_{eq} reductions for NC05, NC10, NC20, and NC30 were 6, 13, 15 and 28%, respectively. For Lao Shan incense, the mean reductions were -2, 17, 18 and 39%, respectively. These results indicate that P-PAH and total BaP_{eq} emissions from incense can be reduced using nano-$CaCO_3$ additive; the reduction increased with increasing amount of nano-$CaCO_3$ additive.

As mentioned, nano-$CaCO_3$ content was 2.68, 5.36, 10.7 and 16.1% in the burning part, respectively, for NC05, NC10, NC20, and NC30, which are less than the means of P-PAH reductions (8, 17, 27 and 40%, respectively) and total BaP_{eq} reductions (2, 15, 16 and 33%, respectively) for the two types of test incense. These results strongly suggest that the addition of nano-$CaCO_3$ significantly reduces P-PAH emissions.

The 16 individual PAHs were divided according to their

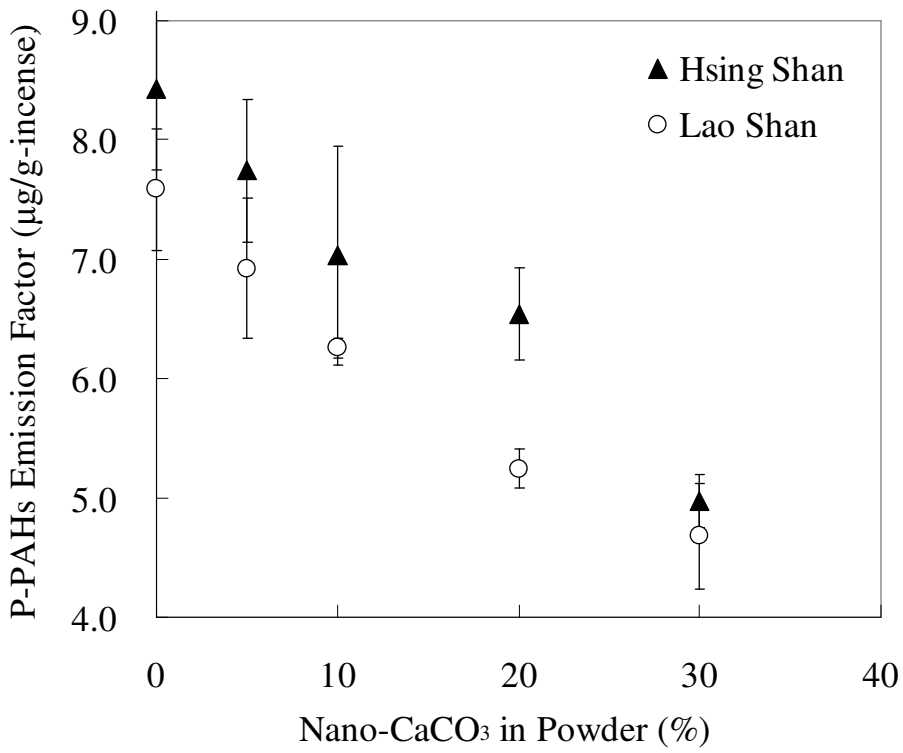

Figure 3. P-PAHs emission factors of test incense for various amounts of nano-$CaCO_3$ additive (each error value equals one standard deviation)

molecular weight into three categories: The LM-PAHs, MM-PAHs and HM-PAHs. Tables 3 and 4 show that the emission factor values for original (NC00) Hsing Shan incense were 1.59, 3.73, and 3.10 µg/g, respectively, accounting for 19, 44 and 37% of total P-PAHs. LM-PAHs, MM-PAHs, and HM-PAHs emission factor values from Hsing Shan incense for NC05, NC10, NC20 and NC30 were 0.49 to 1.61, 2.21 to 3.40, and 2.27 to 2.83 µg/g, respectively, accounting for 10 to 21, 43 to 46 and 36 to 46% of total P-PAHs, and is similar to Lao Shan incense. The PAH emission profiles of the two original types of incense are similar. The results are consistent with our previous study, which found that emission profiles of PAHs from nine types of incense shared a common pattern (Yang et al., 2006).

In addition, Table 4 show that total BaP_{eq} emission factors for orginal (NC00) Hsing Shan incense were 0.005, 0.086, and 1.266 µg/g, respectively, accounting for 0.3, 6.3 and 93.3% of total BaP_{eq}. Total BaP_{eq} of three categories emission factor values from Hsing Shanincense for NC05, NC10, NC20 and NC30 were 0.001 to 0.004, 0.061 to 0.087 and 0.9191 to 190 µg/g, respectively, accounting for 0.1 to 0.3, 6.2 to 6.8 and 92.9 to 93.6% of total BaP_{eq}, and is similar to Lao Shan incense.

The summary of aforementioned results may be attributed to a lower amount of organic wood materials, such as bamboo, adhesive, and wood flour, being burned in incense with nano-$CaCO_3$ additives. Nano-$CaCO_3$ prevented air convection and kept a high temperature at the burning tip, which decreased the smolder effect during incense combustion. Therefore, the addition of nano-$CaCO_3$ efficiently decreases genotoxic P-PAHs. In addition, individual PAH emission profiles of various types of incense are similar and thus independent of nano-$CaCO_3$ content.

PM and PAHs reductions from incense with nano-$CaCO_3$ in Taiwan

Table 5 shows the effect of 10% nano-$CaCO_3$ content in powder on the burning time, burning rate, and emissions of both PM and PAHs after regression analysis. It was found that the addition of 10% nano-$CaCO_3$ reduced the burning time by 16.3 min, increased the burning rate by 11.3 mg/min, reduced PM by 7.30 mg/g, and reduced P-PAHs by 1.03 µg/g and BaP_{eq} by 0.15 µg/g. There are 6.1 million families in Taiwan (Taiwan MOI, 2010), with 45% burning incense twice per day (Lung et al., 2007). If it is assumed that three sticks (the weight of one stick is 1.0 g) are used each time, domestic incense consumption is 6,120 tons. 4,000 tons of incense is used in temples per year (Hu et al., 2009). The total consumption

Table 3. Individual 16 P-PAHs emission factors of test incense for various amounts of nano-$CaCO_3$ additive.

P-PAHs	Hsing Shan incense					Lao Shan incense				
(μg/g-incense)	NC00	NC05	NC10	NC20	NC30	NC00	NC05	NC10	NC20	NC30
Nap	0.08	0.12	0.06	0.06	0.05	0.20	0.13	0.08	0.04	0.04
Acpy	0.11	0.28	0.07	0.18	0.06	0.32	0.22	0.17	0.11	0.11
Acp	0.06	0.04	0.01	0.02	0.01	0.04	0.03	0.02	0.01	0.01
Flu	0.23	0.05	0.02	0.03	0.02	0.06	0.04	0.03	0.03	0.02
Pa	0.77	0.82	0.56	0.56	0.26	0.73	0.64	0.51	0.39	0.47
Ant	0.34	0.31	0.25	0.27	0.10	0.31	0.25	0.25	0.19	0.17
Fl	0.93	0.77	0.76	0.59	0.39	0.66	0.62	0.53	0.41	0.52
Pyr	0.91	0.74	0.76	0.56	0.40	0.66	0.57	0.51	0.39	0.45
BaA	0.72	0.73	0.66	0.61	0.51	0.69	0.86	0.58	0.46	0.59
CHR	1.16	1.15	1.05	1.04	0.90	1.02	0.82	0.93	0.76	0.63
BbF	0.55	0.47	0.49	0.46	0.38	0.45	0.53	0.45	0.41	0.35
BkF	0.30	0.24	0.32	0.26	0.23	0.26	0.24	0.28	0.21	0.10
BaP	0.97	0.87	0.84	0.81	0.71	0.98	0.98	0.79	0.77	0.58
IND	0.57	0.50	0.51	0.50	0.45	0.58	0.53	0.53	0.51	0.34
DBA	0.15	0.20	0.12	0.15	0.10	0.13	0.16	0.11	0.15	0.09
BghiP	0.57	0.46	0.54	0.46	0.41	0.50	0.32	0.46	0.42	0.20
∑LM-PAHs	1.59	1.61	0.98	1.12	0.49	1.66	1.30	1.07	0.77	0.82
∑MM-PAHs	3.73	3.40	3.23	2.79	2.21	3.03	2.87	2.56	2.01	2.19
∑HM-PAHs	3.10	2.73	2.83	2.63	2.27	2.90	2.76	2.63	2.47	1.66
Total PAHs	8.43	7.74	7.03	6.54	4.97	7.59	6.92	6.25	5.25	4.68

P-PAHs: Particle-phase PAHs. LM-PAHs: Low molecular weight PAHs (2 to 3 ring). MM-PAHs: Median molecular weight PAHs (4 rings). HM-PAHs: High molecular weight PAHs (5 to 6 rings)

Table 4. Three categories total BaP_{eq} emission factors and fractions of test incense for various amounts of nano-$CaCO_3$ additive.

	Hsing Shan incense					Lao Shan incense				
	NC00	NC05	NC10	NC20	NC30	NC00	NC05	NC10	NC20	NC30
Total BaP_{eq} (μg/g)	1.36	1.28	1.18	1.15	0.98	1.33	1.37	1.11	1.10	0.82
LM-PAHs	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MM-PAHs	0.09	0.09	0.08	0.07	0.06	0.08	0.10	0.07	0.05	0.07
HM-PAHs	1.27	1.19	1.10	1.08	0.92	1.25	1.27	1.04	1.04	0.75
Total BaP_{eq} fraction (%)										
LM-PAHs	0.3	0.3	0.3	0.3	0.1	0.3	0.3	0.3	0.2	0.3
MM-PAHs	6.3	6.8	6.6	6.3	6.2	6.0	7.0	6.2	4.9	8.1
HM-PAHs	93.3	92.9	93.2	93.4	93.6	93.6	92.8	93.5	94.8	91.6

BaP_{eq}: Benzo[a]pyrene equivalent. LM-PAHs: Low molecular weight PAHs (2 to 3 ring). MM-PAHs: Median molecular weight PAHs (4 rings). HM-PAHs: High Molecular Weight PAHs (5 to 6 rings).

of incense in Taiwan is thus 10,012 tons per year. Therefore, using incense with 10% nano-$CaCO_3$ additive instead of traditional incense can reduce PM by73.0 tons, P-PAHs by 10.3 kg, and BaP_{eq} by 1.5 kg.

Conclusion

This study indicates that the addition of nano-$CaCO_3$, from 10.0 to 30.0% in powder, for two types of commonly used incense decreased PM emissions by 21 to 59%, P-PAH emissions by 17 to 41% and particle phase-BaP_{eq} by 13 to 39%. These results may be attributed to nano-$CaCO_3$ having refractory characteristics, which has high specific surface and thermal insulation at there placed organic wood materials, such as bamboo, adhesive, and wood flour, that reduce air pollutants generation during incense combustion.

It was also found that adding 10% nano-$CaCO_3$ in

Table 5. Effect of 10% nano-$CaCO_3$ additive on combustion characteristics and emissions after regression analysis.

	Hsing Shan incense	Lao Shan incense	Average
Burning time (min)	-17.0 (0.94)[a]	-15.6 (0.97)	-16.3
Burning rate (mg/min)	+11.7 (0.99)	+10.9 (0.99)	+11.3
Particle (mg/g)	-7.43 (0.96)	-7.17 (0.98)	-7.30
P-PAHs (µg/g)	-1.07 (0.97)	-0.98 (0.97)	-1.03
Total-BaP_{eq} (µg/g)	-0.12 (0.95)	-0.17 (0.88)	-0.15

[a]: r^2 value of linear regression analysis.

incense powder can reduce PM by 73.0 tons, P-PAHs by 10.3 kg, and BaP_{eq} by 1.5 kg emissions by burning incense in Taiwan per year. These reductions seem very small when compared to entire air pollutants in Taiwan. Nevertheless, the pollutants by burning incense are very close to people. Although the quality of incense, in terms of fragrance and burning time, may be slightly compromised due to enhanced burning efficiency; the addition of nano-$CaCO_3$ effectively reduces emissions that are harmful to human health. The findings of this study may serve as a guide for producing safer incense.

It is well known that nano-$CaCO_3$ has high specific surface and thermal insulation.

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