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Emission of volatile organic compounds from religious and ritual activities in India

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Abstract Worshipping activity is a customary practice related with many religions and cultures in various Asian countries, including India. Smoke from incense burning in religious and ritual places produces a large number of health-damaging and carcinogenic air pollutants include volatile organic compounds (VOCs) such as formaldehyde, benzene, 1,3 butadiene, styrene, etc. This study evaluates real-world VOCs emission conditions in contrast to other studies that examined emissions from specific types of incense or biomass material. Sampling was conducted at four different religious places in Raipur City, District Raipur, Chhattisgarh, India: (1) Hindu temples, (2) Muslim graveyards (holy shrines), (3) Buddhist temples, and (4) marriage ceremony. Concentrations of selected VOCs, respirable particulate matter (aerodynamic diameter, <5 μm), carbon dioxide, and carbon monoxide were sampled from the smoke plumes. Benzene has shown highest emission factor (EF) among selected volatile organic compounds in all places. All the selected religious and ritual venues have shown different pattern of VOC EFs compared to laboratory-based controlled chamber studies.

Keywords Emission factor · Volatile organic compounds · Indoor air pollution · Religious and ritual places

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Introduction

Volatile organic compounds (VOCs) participate in the atmospheric photochemical reactions forming secondary organic aerosol on oxidation (Platnick and Twomey 1994; Feingold and Morley 2003) and ozone in the presence of NOx (Pun et al. 2002; Pinto et al. 2007). It has been estimated that environmental damage due to the precursors of O_3 (VOC and NOx) emissions is roughly $1,000/Mg VOCs (Rable and Eyre 1998). The adverse health effects of certain VOC include chronic obstructive pulmonary disease, bronchial asthma, systolic plus diastolic hypertension, and lung cancer (Guo et al. 2004; Arif and Shah 2007). Selected VOCs have been quantified in various environments including ambient air (Kumar and Viden 2007; Srivastava et al. 2006); residential–indoor air (Beck et al. 2007), workplace–indoors (Tovalin-Ahumada and Whitehead 2007), and personal exposures (Tovalin-Ahumada and Whitehead 2007; Saborit et al. 2009). Apart from atmospheric VOC studies, emission estimation from different combustion/noncombustion activities viz. biomass burning (Maleknia et al. 2009), vehicular activities (Zielinska et al. 1996; Cai and Xie 2009), indoor cooking activities (Pandit et al. 2001; Taneja et al. 2008; Massey et al. 2013), cigarette smoke (Polzin et al. 2007), and incense smoke (See and Balasubramanian 2011) has also been documented. Recent estimates of the global emission of VOCs into the atmosphere range from about 1,200 to 1,600 TgC year^{-1} (Goldstein and Galbally 2007; Reimann and Lewis 2007).

Worshipping activity is a customary practice related with many religions and cultures in various Asian countries, including India. Smoke from incense burning in religious and ritual places produces a large number of health-damaging and carcinogenic air pollutants including respirable particulate matter, nitrogen and sulfur oxides, and VOCs such as formaldehyde, benzene, 1,3 butadiene, styrene, toluene, ethyl benzene, xylene, chloroform, etc. (Lee and Wang 2004). It has also been observed that temple workers were exposed to higher concentration of benzene (45.90 μg m^{-3}) and 1,3-butadiene (11.29 μg m^{-3}) than those of control workers(Navasumrit et al. 2008). Combustion material used in Indian religious and ritual activities are different from those used in others countries, where mostly synthetic incense material is used (Lee and Wang 2004). Therefore, Indian religious combustion activities attribute diverse characteristics of emissions. Additionally, household biomass combustion for cooking purposes is of different character from that of religious activities. For Indian religious and ritual performances, synthetic organic and natural biomaterials in various proportions are burnt. In addition, sprinkling of liquid ingredients (oils and holy waters) over these combustion materials in religious activities (Table 1) result in frequent variation in smoldering and flaming episodes.

In India, large amount of VOCs is emitted from various burning practices such as rice straw burning, agricultural crop residue burning, fossil fuels combustion in residential and industrial sectors, transportation, forest fires, and other burning activities(Padhy and Varshney 2005; Srivastava et al. 2006; Gokhale et al. 2008). The emission factors of VOCs from various religious burning activities were not yet characterized. The present study has been focused on development of emission factors of selected VOCs released during combustion activities of major religious performances in India. The emission factors for carbon dioxide (CO_2), carbon monoxide (CO), respirable particulate matter (RPM; particle size, less than 5 μm), and volatile organic compounds from four different types of Indian religious places were developed in this study.

Materials and method

Study area

There are ~3.0 million religious places of worship in India and 10 million marriages per year (Census 2011). Table 1 list the religious places in Raipur, Chhattisgarh located in central India that was sampled for this study. In a Hindu marriage, the couple transits seven circuits around a Holy Fire fueled by the materials described in Table 1. Different religion-oriented worship places (Hindu temples, Muslim graveyards, and Buddhist temples) are also burning different kinds of bio- and synthetic materials described in Table 1. This study evaluates real-world emission conditions in contrast to other studies that examined emissions from specific types of incense (Lee and Wang 2004) or biomass material (Janhall et al. 2010). Sampling was conducted at four different religious places in Raipur city, District Raipur, Chhattisgarh, India: (1) Hindu temples, (2) Muslim graveyards (Holy shrines), (3) Buddhist temples, and (4) marriage ceremony. Three separate examples of each of these four religious venues were sampled when materials were burned during listed frequencies of events (Table 1) in respective venues. Table 1 also describes the materials burned and a visual evaluation of the extent to which the burning was dominated by flaming (visible fire) or smoldering (visible smoke and embers) emissions. Concentrations of selected VOCs, RPM (aerodynamic diameter, <5 μm), CO_2, and CO were sampled from the smoke plumes. Before the in-plume sampling, background samples of gaseous pollutants and RPM were measured at each location for subtraction from the in-plume concentrations.

Emission factor development

The emission factor, generally expressed in units of gram per kilogram, is generally calculated by dividing the mass of emissions by the mass of the dry material consumed by fire (Andreae and Merlet 2001). It is the mass of pollutants emitted per unit mass of dry material

Table 1 Sampling in religious places in Raipur

Sampling sites	Frequency (*n*)	Sampling times (min)	Distance of VOCs sampler from sources (cm)	Main ingredients	Location	Combustion types
Marriage ceremony	18	215–320	80	Wood, cow dung cakes, cow urine, clarified semifluid butter, Hawan (worship of fire), material (rice, barley, sesame, vermillion powder, turmeric powder, camphor, cardamom, betel nut, betel leaf, clove, etc.)	Indoor	Flaming and smoldering
Muslim graveyards	12	120–150	38	Incense sticks and Styrax benzoin	Indoor	Smoldering
Buddhist temple	8	120–180	35.5	Incense sticks and candles	Indoor	Smoldering was dominant
Hindu temple	26	120–150	60	Clarified semifluid butter, vegetable oil, vermillion powder, and cotton	Indoor	Flaming

consumed by fire. The equation for the calculation of emission factor is as follows:

$$\mathrm{EF}_j\left(\mathrm{g.\ kg}^{-1}\right) = \frac{\Delta \mathrm{C}_j \mathrm{X}\ 1,000\left(\mathrm{g.\ kg}^{-1}\right)\mathrm{X\ C}_{\mathrm{fraction}}}{\left(\Delta\mathrm{CO}_2\mathrm{-C} + \Delta\mathrm{CO{-}C} + \Delta\mathrm{THC{-}C} + \Delta\mathrm{PM{-}C}\right)}$$

where, EF_i is the emission factor of pollutant x in gram per kilogram, ΔC_i is the background-corrected concentration of pollutant x in milligram per cubic meter, ΔCO_2-C is the mass fraction of C in CO_2 in milligram per cubic meter, ΔCO-C is the mass fraction of C in CO in milligram per cubic meter, ΔTHC-C mass fraction of C in total hydrocarbon in milligram per cubic meter, ΔPM-C is the mass fraction of C in particulate matter in milligram per cubic meter, and C_{fraction} is the carbon content in dry material.

The THC and PM carbon are typically <<1 % of the $CO+CO_2$ and can be neglected. Emission factors determined by this method are summarized in Tables 2 and 3.

C_{fraction} in the dry matter was determined by weighted ratio of different ingredients (biomass and synthetics) used in burning processes of selected religious activities. One of the major ingredients used in all activities is the bark of *Shorea rodusta* and mangifera trees that has carbon contents of 36.8–50 % as compared to other regional species (32.4 %; Maharjan 2012). Other major ingredients are cow dung and urine having carbon content of 38.6–42.5 % (Haq and Haq 2006), grains (43.4–44.2 %; Dhammapala et al. 2006, 2007), and incense matter (43.8±3.3 %; Yang et al. 2007). The resulting C_{fraction} of different burning mixtures of bio/synthetic matters in selected religious activities were computed: 55 % for Hindu marriage ceremony, 45 % for Muslim graveyards, 55 % for Buddhist temples, and 68 % for Hindu temples.

Sampling and analysis

CO_2 and CO monitors were installed along with VOCs passive samplers above the smoke plume. Volatile organic compounds emitted during burning of material in selected religious places were passively collected using Radiello VOC samplers (Supelco Analytical), consisting of stainless steel mesh cylinders (3×8 μm mesh, 4.8 mm diameter×60 mm length) packed with Carbograph4 (350 mg). The cartridges were deployed in the diffusive sampling bodies according to the manufacturer's instructions (Radiello 2010). Passive samplers were designed as portable and noiseless devices without a power supply, suitable for measurement of indoor air pollution (Busoon et al. 2003). Samplers were deployed over smoke plume at different heights. Fourteen volatile organic compounds were measured in burning activities in religious places, namely: *n*-hexane, benzene, cyclohexane, *n*-heptane, toluene, *n*-octane, ethylbenzene, *m*,*p*-xylene, styrene, *o*-xylene, *n*-nonane, *n*-decane, 1,2,4-trimethylbenzene, and *n*-undecane. All Radiello samples were analyzed by the thermal desorption cryogenic preconcentration method, followed by high-resolution gas chromatographic

Table 2 Emission factor (in gram per kilogram) of measured gaseous pollutants and respirable particulate matter for Indian different religious based burning activities

Species Sites	CO_2	CO	RPM
Marriage ceremony	2,711.70±274.49	190.36±23.76	47.38±5.90
Muslim graveyards	352.20±6.38	78.78±11.82	30.69±2.64
Buddhist temple	1,240.98±159.88	213.39±26.94	33.09±2.76
Hindu temple	687.57±98.78	1.72±0.23	18.12±2.05

separation and mass spectrometric detection (GC/MS) of individual compounds. The Gerstel Thermal Desorption System (TDS) unit, equipped with Cooled Injection System (CIS) and 20-position autosampler, attached to the Varian Saturn 2000 GC/MS, was used for the purpose of sample desorption and cryogenic preconcentration (Mason et al. 2011). Initial desorption was set for 10 min at 320 °C before transfer to a Tenax TA trap cooled to −150 °C. Sample was split 20:1 in order to reduce analytical loading in the MS. A 60-m (0.32 mm i.d., 0.25 mm film thickness) DB-1 capillary column (J&W Scientific, Inc.) was employed to achieve separation of the target species. The chromatographic conditions were as follows: injection temperature, 240 °C; initial column temperature, 40 °C; held for 3 min and then programmed at 3 °C/min to 120 °C, followed by 20 °C/min to 280 °C.

The instrument was calibrated by thermally desorbing glass tubes packed with Carbograph 4. The calibration tubes were loaded with a certified standard [VOCs from PAMS (Photochemical Assessment Monitoring Station, Environmental Protection Agency (EPA)) standard Restek, Inc., and BTEX in nitrogen, Scott Specialty Gases] by measuring the volume passing through the tubes. Four different concentrations (plus one blank) were used to construct calibration curves.

RPM was sampled onto 47-mm diameter quartz fiber filters [Whatman QMA 1851-047(grade number of Whatman filter paper sequentially numbered

Table 3 Emission factor (in gram per kilogram) of measured volatile organic compounds for Indian different religious based burning activities

Sites Species	Marriage ceremony	Muslim graveyard	Buddhist temple	Hindu temple	Reported value
n-Hexane	0.013±0.002	0.001±0.0001	0.009±0.001	0.0003±0.0001	–
Benzene	1.06±0.12	0.243±0.026	0.893±0.125	0.011±0.002	0.489 (Lee and Wang 2004)
Cyclohexane	0.024±0.003	0.005±0.0006	0.064±0.008	0.0006±0.0001	–
n-Heptane	0.19±0.03	0.020±0.003	0.229±0.037	0.001±0.0001	–
Toluene	0.479±0.047	0.091±0.015	0.570±0.096	0.006±0.0009	0.273 (Lee and Wang 2004)
n-Octane	0.525±0.029	0.012±0.001	0.203±0.023	0.005±0.0002	–
Ethylbenzene	0.084±0.007	0.013±0.001	0.081±0.005	0.002±0.0003	0.172 (Lee and Wang 2004)
m,*p*-Xylene	0.137±0.013	0.026±0.003	0.20±0.04	0.007±0.0003	0.029(Lee and Wang 2004)
Styrene	0.653±0.105	0.131±0.021	0.79±0.13	0.009±0.0005	0.028 (Lee and Wang 2004)
o-Xylene	0.094±0.008	0.011±0.001	0.091±0.016	0.003±0.0001	0.117 (Lee and Wang 2004)
n-Nonane	0.687±0.084	0.004±0.0002	0.196±0.04	0.006±0.0007	
n-Decane	0.445±0.089	0.006±0.0007	0.303±0.024	0.028±0.004	
1,2,4-Trimethyl benzene	0.141±0.023	0.015±0.003	0.223±0.031	0.007±0.001	
n-Undecane	0.422±0.037	0.002±0.0004	0.156±0.027	0.009±0.001	

according to EPA standards)]with three Envirotech Model APM 821 samplers equipped with a 5-µm 50 % cut-point cyclone inlet at an average flow rate of 2.0 L min^{-1}. Three sampling units have been used in the emitted plume to evaluate field uncertainties of selected pollution parameters. The sampler inlets were moved to remain within the visible smoke plume. Quartz fiber filters were prebaked at 450 °C for 5 h before sampling to remove residual carbon (Chow 1995), were equilibrated in a controlled chamber (relative humidity, 45–55 %; temperature, 22–26 °C) for 24 h, and weighed with a single pan top loading digital balance (Denver, Model, TB-2150) with ±10 µg precision prior to and after sampling. Samples were stored at −4 °C prior to further chemical analysis. Sample durations and mass loading/filter were: 215–320 min and 5.8–6.01 mg/filter (marriage palaces), 120–150 min and 4.1–10.9 (in milligram per filter; Muslim holy shrines), 120–180 min and 2.94–3.21 (in milligram per filter; Buddhist temples), and 120–150 min and 0.16–0.3 (in milligram per filter; Hindu temples).

Five-minute CO concentrations were measured with a nondispersive infrared (NDIR; Langan Products Inc., San Francisco, CA, USA; model T15v) and CO2 was measured with a collocated NDIR instrument (AZ Instrument Corporation, Taiwan; model AZ 7755). Probes were placed in the smoke plumes next to the RSP inlet (Lee and Wang 2004).

Results and discussion

The highest CO_2 EF was 2,711.70±274.49 g kg^{-1} for the marriage ceremony, while the lowest 352.20±6.38 g kg^{-1} was found for the Muslim graveyards. The emission factor of CO_2 in Muslim graveyards is similar (352.16±355.68) to that reported in a previous study (Wang et al. 2007). During the marriage ceremony, biomass burning occurred mostly in the flaming phase. The CO EF was highest at the Buddhist temple (213.39±26.94 g kg^{-1}) with the lowest CO EF of 1.72±0.23 g kg^{-1} found for Hindu temples. This might be due to different durations of flaming and smoldering episodes; Buddhist temple burning activities have shown higher duration of smoldering episodes while Hindu temples have shown higher flaming duration. Burning events with major ingredients of incense material (Muslim graveyards and Buddhist temples) have shown comparable EF values of CO_2 and CO to earlier work on laboratory scale (Wang et al. 2007). But EFs of both CO and CO_2 in other selected religious and ritual places are entirely different from that documented

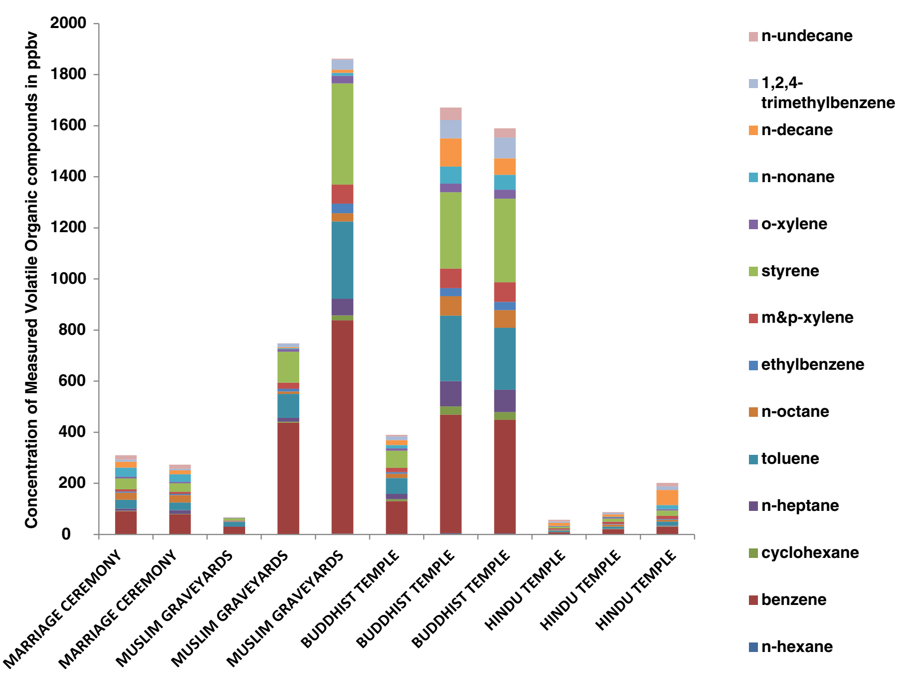

Fig. 1 Concentration (parts per billion volume) of measured volatile organic compounds for religious based burning activities at Raipur

for burning of specific ingredients in laboratory modeling scale. RPM EFs were highest for the marriage ceremony, averaging 47.38±5.90 g kg^{-1} and low8-est for the Hindu temple (18.12±2.05 g kg^{-1}). RPM EFs for Buddhist temple are similar to Muslim graveyards due to similarity in the combustion processes and comparable to earlier reported EFs for incense burning (Wang et al. 2007). The EF values for CO_2, CO, and RPM are shown in Table 2.

Emission factors of selected VOCs for representative religious places, i.e., marriage ceremony, Muslim graveyards, Buddhist temple, and Hindu temple are given in Table 3. Graphical form of concentration of selected VOCs is shown in Fig. 1. It can be seen that benzene has the highest emission factor among volatile organic compounds in all places. The average emission factor of benzene was 1.06±0.12 kg^{-1} (marriage ceremony), 0.243±0.026 g kg^{-1} (Muslim graveyards), 0.893±0.125 g kg^{-1} (Buddhist temple), and 0.011±0.002 g kg^{-1} (Hindu temple), which is comparable to the reported values from incense burning (0.489±0.376 g kg^{-1}; Lee and Wang 2004) crop residue (0.15±0.04 g kg^{-1}), tropical forest (0.36±0.16 g kg^{-1}), savanna burning (0.20±0.084 g kg^{-1}; Akagi et al. 2011), savanna and grassland burning (0.039±0.045 g kg^{-1}), biofuel burning (0.04 g kg^{-1}), charcoal (0.063 g kg^{-1}), and agricultural residue burning (0.05 g kg^{-1}; Andreae and Merlet 2001). Benzene EFs from marriage ceremony is, on average, two times higher than common incense burning in temples (Lee and Wang 2004). The marriage ceremony performs combustion activities using a larger variety of synthetic and natural biomaterial including cow dung cakes, cow urine, and semiclarified butter due to ritual belief of holy cleaning of surrounding atmosphere. Dung and urine discharged by cow are considered as Holy matter due to worship of cows among Hindus in India and it is mandatory to use these materials during religious burning processes. Dung burned mostly in smoldering conditions and flaming episodes occurred due to other ingredients such as wood, dry leaves, oils, and camphor. All these materials produced large amount of volatile organic compounds during the burning process. The combustion of human body produced a variety of *n*-alkanes, alkenes, light aromatics, and cyclic organic compounds (DeHaan et al. 2004).

The Hindu temple has the lowest emission factors for all measured volatile organic compounds as compared with marriage ceremony, Muslim graveyards, and Buddhist temple. In the Hindu temple, vegetable oil and cotton are used for burning purposes and these materials are burnt during the flaming stage which may produce lesser amount of VOC. Marriage ceremony and Buddhist temple show different pattern of emission factor of measured volatile organic compounds compared to that observed in Hindu temples. When comparing the marriage ceremony and Buddhist temple, it was observed that emission factors of *n*-hexane, *n*-octane, ethylbenzene, *o*-xylene, *n*-nonane, *n*-decane, and *n*-undecane are highest in marriage ceremony and the lowest in Buddhist temple (Table 3). This is because in marriage ceremony, wood, cow dung, cow urine, semiclarified butter milk, and Hawan material (rice, barley, sesame, vermillion powder, turmeric powder, camphor, cardamom, betel nut, betel leaf, clove, etc.) are used and frequent changes in flaming and smoldering phases occur during combustion. In contrast, *n*-heptane, cyclohexane, toluene, *m-p* xylene, styrene, and 1,2,4-trimethylbenzene show highest emission factors in Buddhist temple with lowest EFs in marriage ceremony. These are cyclic and aromatic compounds. In Buddhist temple, candles and incense sticks were used in worshipping activity. Generally, incense sticks are made from charcoal, glue powder, aromatic wood and bark, and synthetic chemicals which are used in the perfume industry (Jetter et al. 2002). Aroma used in incense sticks could be a source of aromatic compounds. It has been observed that emission factor of measured volatile organic compounds (benzene, toluene, *m-p* xylene, and styrene) emitted from burning of incense sticks are higher than previously reported emission factor of volatile organic compounds emitted from incense sticks burning (Lee and Wang 2004). The emission factors of measured VOCs have been found to be lower in Muslim graveyards compared to all other places except the Hindu temple. In Muslim graveyards, incense sticks and Styrax benzoin (Lobn) are used. Styrax benzoin is composed mainly of sulfur-containing compounds, which were not measured in the present study.

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