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Estimating emissions from open burning of municipal solid waste in municipalities of Nepal

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ABSTRACT

Open burning of municipal solid waste (MSW) is a poorly-characterized and frequently-underestimated source of air pollution in developing countries. This paper estimates the quantity of MSW that was burned in five erstwhile municipalities of the Kathmandu valley, Nepal. A household survey, a transect walk survey, an experiment to measure the fraction of waste that is combustible, a survey on fraction of population burning waste outside their houses, and a survey of the fraction of MSW burned at dump sites were performed in this study, whereas burning/oxidation efficiency, municipal populations, MSW generation rates, and emission factors were derived from the literature. The total mass of MSW burned during 2016 is estimated to be 7400 tons (i.e., 20 tons/day), which was of 3% of the total MSW generated in the valley municipalities that year. This exceeds Government estimates by a factor of three. Multiplying the burned MSW mass by emission factors, the air pollutant emissions are estimated as $PM_{2.5}$ 55 tons (OC 42 tons and EC 1.4 tons), PM_{10} 60 tons, BC 25 tons, CO_2 11,900 tons, CH_4 30 tons, SO_2 5.0 tons, NO_x 19.2 tons, CO 630 tons, NMVOC 112 tons, and NH_3 5.7 tons per year. Open burning of MSW can trigger health impacts such as acute and chronic respiratory disease, heart diseases, and allergic hypersensitivity, in addition to impacts on local climate. Improved waste-segregation practices at the source and waste-collection systems throughout the valley are needed to mitigate this pollution source and its effects.

1. Introduction

Solid waste management (SWM) has become a major concern, especially in urban areas of developing countries. Many municipalities are experiencing extreme environmental degradation as well as public health risks due to ill-timed waste management and unsanitary disposal practices (Alam et al., 2008; Nagpure et al., 2015). Recently, the open burning of solid waste was implicated as a major cause for soiling the Taj Mahal and impairing the health of Agra residents (Lal et al., 2016). In Nepal, population growth, rapid expansion of sprawling urban municipalities, increasing amounts of industrial and commercial activity, and rising consumption of packaged goods has resulted in severe air and water quality issues, poor sanitation, and the spread of diseases (Alam et al., 2008; Dangi, 2009; Pokhrel and Vivaraghavan, 2005).

At an elevation of 1400 m, the bowl-shaped Kathmandu valley lies at the foothills of the Himalayas and is surrounded by mountains and forests. The total urban area of Kathmandu valley is 96.68 km^2 (KVDA, 2017) and this area has the highest population density in Nepal. The valley contains five densely-inhabited urban centres which were previously designated as municipalities: Kathmandu Metropolitan City (KMC), Lalitpur Sub-Metropolitan City (LSMC), Bhaktapur, Kirtipur and Madhyapur Thimi. Around the time of study, the Government of Nepal designated 16 municipalities (dividing many of the earlier five into smaller areas) in the valley partly in response to the booming urban population (KVDA, 2017).

Fig. 1 contains a map of the five original municipalities referred to throughout this study and their location within Nepal. KMC is home to the nation's capital and is the most populated municipality in Nepal with an area of 49.45 km^2 (CBS, 2013) subdivided into 35 wards (KMC, 2014). LSMC was the country's third most populous municipality and is located in the south-central part of the valley, covering an area of 24.94 km^2 that was subdivided into 30 wards (LSMC, 2016). Bhaktapur is an ancient city in the eastern

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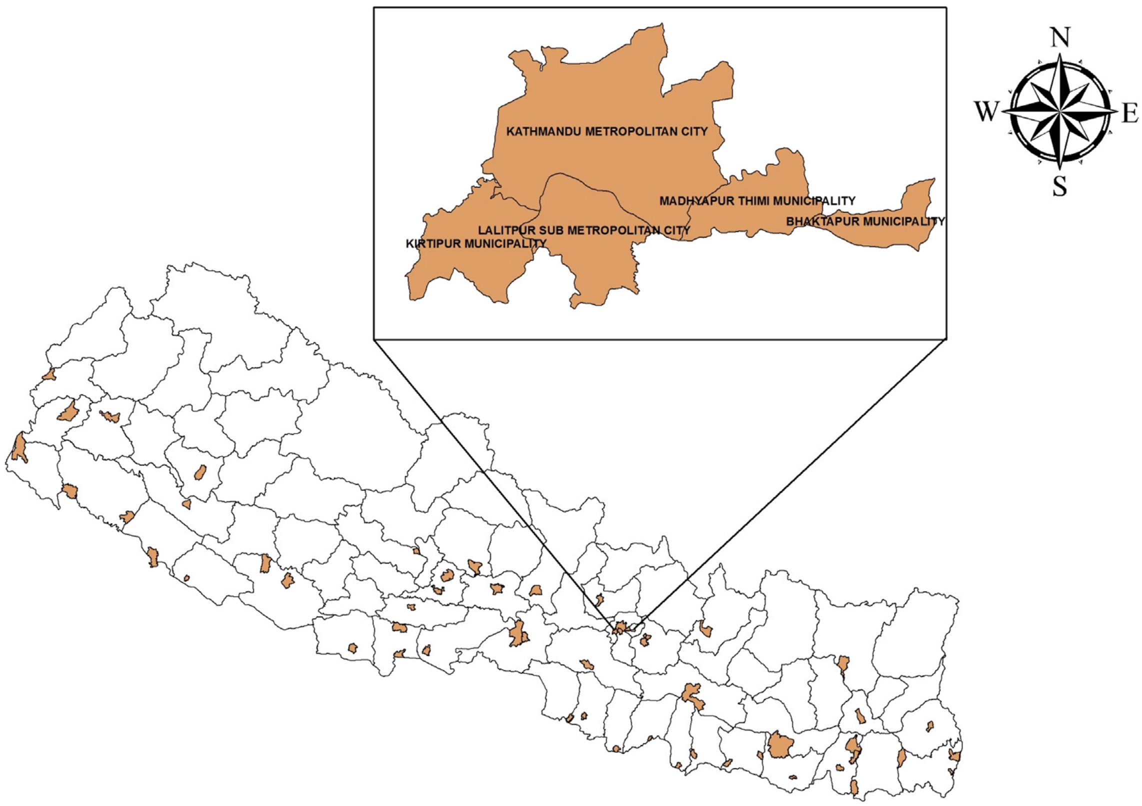

Fig. 1. Map of Nepal with political boundaries delineating the 75 districts (mostly white) and the 58 old municipalities (orange). The enlarged portion shows the five Kathmandu valley municipalities where this study focused. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

part of the valley, 16 km east of the KMC centre. It was divided into 17 wards and covered only 6.88 km^2 (Bhaktapur Municipality, 2016). Kirtipur municipality is less populated than the others and has grown around another ancient kingdom southwest of the KMC centre. Madhyapur Thimi is the newest of the five municipalities, which resulted from population infill between Bhaktapur and KMC.

Although Kathmandu valley is the most developed place in Nepal and covers the largest number of commercial and institutional sectors, the SWM in much of the valley remains unsatisfactory. In Kathmandu, SWM has become a chronic problem that has challenged and evaded development efforts for decades (Dangi, 2009). Many statistics related to SWM in Kathmandu valley are highly uncertain, as evidenced by the large variability across studies (Nippon Koei Co. Ltd. and Yachiyo Engineering Co. Ltd., 2005; SWMRMC, 2008; Dangi et al., 2011). A brief summary is provided here with the acknowledgement that these data are not necessarily consistent with each other.

About 50% of the waste from municipalities of Kathmandu valley is generated by households, 43% from commercial, 6% from the institutional, and relatively little (1%) from parks and gardens, street sweeping, and from neighboring villages (ADB, 2013). In 2012, the average per capita municipal solid waste generation rates (MSWGR) for KMC, LSMC, Kirtipur, Bhaktapur and Madhyapur Thimi were 0.46 kg/capita/day (kcd), 0.37 kcd, 0.25 kcd, 0.35 kcd, and 0.27 kcd, respectively. The most recent study (SWMTSC, 2015) showed the average MSWGR for a sub-urban neighborhood of KMC (i.e., Budanilkantha) and LSMC (i.e., Mahalaxmi/Gwarko) in 2014 to be 0.48 kcd and 0.36 kcd, respectively. Comparing ADB (2013) to the past studies (Nippon Koei Co. Ltd. and Yachiyo Engineering Co. Ltd., 2005; Alam et al., 2008), the per capita MSWGR has increased steadily in the valley municipalities. This is likely due to increased consumption of packaged goods and gradual rise of commercial and industrial activities. Moreover, a research-grade study by Dangi et al. (2011) indicates that the MSWGR is even higher than all of the aforementioned reports.

Although 71% of MSW generated in Kathmandu is organic (Dangi et al., 2011), very few neighborhoods have systems in place to compost this material (Sherpa, 2017). Within the valley municipalities, only 35.3% of waste from Kirtipur, Madhyapur Thimi (52.2%), LSMC (71.2%), Bhaktapur (86.5%) and KMC (86.9%) are collected (ADB, 2013). The situation in other low-income countries appears to be similarly abysmal despite the sizeable expenditure of financial resources on SWM (World Bank, 2012; Hazra and Goel, 2009). At present, urban areas receive more attention for MSW open burning because they are highly populated (Wang et al., 2017).

Large quantities of uncollected waste can be found along the banks of urban waterways such as Bagmati and Bishnumati (Pokhrel and Vivaraghavan, 2005). The water from these rivers is used for domestic purpose, cultivating agriculture and also has religious significance for Hindus. Sometimes uncollected waste is found in close proximity to small-scale agricultural fields where it contaminates the food supply. In communities that are far from waste-collection routes (Subedi, 2016), refuse is commonly dumped in privately-owned lots that are neither developed nor maintained (Bajracharya, 2016). Any waste that remains uncollected after a few weeks of biodegradation emits a foul odor, prompting nearby residents to burn it (Bajracharya, 2016; Sherchan, 2016).

At this point, it is useful to note that the primary issue discussed in this paper is from MSW that is burned in the open, where combustion conditions (i.e., low temperature, suboptimal air-to-fuel ratio, high moisture content) are favorable to pollutant formation (Wiedinmyer et al., 2014). This paper provides no commentary about the high-temperature, carefully-controlled incineration that is practiced in some developed countries. Open burning of MSW has a major impact on human health because the emitted smoke contains life-threatening particulate matter (PM) enriched in organic carbon (OC) and elemental carbon (EC), carcinogenic dioxins, and numerous other harmful pollutants like nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), non-methane volatile organic compound (NMVOC) (Nagpure et al., 2015; Guttikunda et al., 2014; Guttikunda, 2007; Hodzic et al., 2012; Wiedinmyer et al., 2014; Pokhrel and Vivaraghavan, 2005). High exposure to PM may lead to respiratory and cardiovascular disease, cancer and adverse birth outcomes (McDonnell et al., 2000). It also exacerbates local/regional warming because the carbon dioxide (CO_2) and black carbon (BC) emitted from burning both have a high global warming potential. Even if it is dumped and never burned, the gradual degradation of MSW emits methane (CH_4) which is another potent greenhouse gas. MSW open burning also emits ammonia (NH_3) which can enhance the formation of PM in the atmosphere.

Unlike vehicle exhaust and industrial emissions, the common public and elected officials are relatively unaware of the significance and harmful impacts of open burning (Sherchan, 2016). In the few emission inventories that have been made, open burning of MSW is either completely neglected (Pradhan et al., 2012) or very crudely estimated (Wiedinmyer et al., 2014; Gautam, 2006). This is mainly because of the difficulties and large uncertainty in estimating how much MSW is actually burned (Nagpure et al., 2015). The only urban-scale estimate of emissions from open burning of MSW in Kathmandu was made a decade ago and it arbitrarily assumed that 1% of the waste generated is burned (Gautam, 2006). Other sources of uncertainties are: (i) emissions factors; (ii) activity parameters such as the fraction of population that burns their waste and the fraction of waste that is combustible; and (iii) spatial allocation of waste-burning activities. The purpose of the present study is to constrain some of these uncertainties so that the importance of MSW burning relative to other air pollution sources in Kathmandu Valley may be better understood.

2. Data and methods

This study estimates the MSW open burning in selected urban and sub-urban neighborhoods of Kathmandu valley, following a method that was successful in Delhi and Agra (Nagpure et al., 2015).

2.1. Preparation of field surveyors

Surveyors selected for this study received an orientation from the project scientists. A pilot-scale survey was conducted and repeated until the surveyors were confident and skilled enough to collect their field data independently.

A field study was conducted from April to June 2016 in seven selected portions of KMC including Budanilkantha, LSMC, and Bhaktapur municipality. The study areas included Kalimati/Dallu (core) and Baneshwor (core) of KMC; Budanilkantha (sub-urban); Lagankhel (core) and Mahalaxmi/Gwarko (sub-urban) of LSMC; and Sukuldhoka/Durbar square (core) and Kamalbinayak/Chyamasingha (sub-urban) of Bhaktapur municipality. Within these seven study areas, household surveys and transect walks were conducted along a total of 19 different routes (Fig. 2).

2.2. Estimation of the waste combustible fraction

The field based experiment on waste combustible fraction (δ) was carried out using five samples of MSW found in Kirtipur near Tribhuvan University. The samples were the mixture of household and commercial waste. First, the composition of each pile was noted by visual inspection. Second, initial mass of MSW was measured using a digital weighing balance. Third, the volume of each MSW pile was determined using a measuring tape and stick (e.g., length, width and height). Fourth, the different waste piles were ignited and carefully monitored until the combustible material had turned to ash. Fifth, the volume of each pile after combustion was measured as described above. Lastly, the burnt trash (ash) and the residual trash were segregated carefully and their masses were measured separately.

The burnt mass of MSW was calculated by subtracting the mass of residual trash left after combustion from the total initial mass. The ratio of burnt mass of MSW to total initial mass of MSW is referred to as the waste combustible fraction (IPCC, 2006).

$$\delta = \frac{\text{Burnt Mass of Trash}}{\text{Total initial mass of Trash}} \tag{1}$$

This experimentally-derived parameter was used in the subsequent calculations of MSW open burning.

2.3. Transect walks

In each of the seven study areas, the available major pathways to access the market centre were selected as routes for the transect walks. A distance-sampling approach (i.e., line transect method) was adopted (Nagpure et al., 2015) along each of the 19 routes. Each time a pile of waste was encountered along a transect, the surveying team recorded the geographical coordinates of that pile, and measured the dimensions (i.e., length, breadth and height) of the entire pile so that the total volume could be estimated. The study team took a digital photograph of each waste pile and recorded the time at which it was observed. A few days later, the identical transect walk was repeated a second time to determine whether some of the unburned waste piles were being collected or burned to ash and if new waste piles were introduced. The total number of waste piles was the sum of initial waste piles number from the first transect walk and new waste piles found during the second transect walk.

2.4. Household survey

While traversing each study route and observing waste piles, household surveys were also conducted. Thus, the sample size was determined based on the number of routes, household density and the size/length of each routes of urban core and sub-urban area. On routes with a sparse settlement pattern, every fifth household was selected for the survey starting with the first household along each route (i.e., 1, 6, 11, etc.). Along more densely-populated routes, approximately every tenth household was surveyed (i.e., 1, 11, 21, etc.). In this manner, a total of 179 households were surveyed (29, 35, 28, 16, 25, 23 and 23 in Kalimati/Dallu, Baneshwor, Budanilkantha, Lagankhel, Mahalaxmi/Gwarko, Bhaktapur core, and Bhaktapur sub urban respectively). Residents reported the number of occupants in their household, frequency of waste collection from their home, and their most common waste-disposal practices (e.g., dump, burn, compost, and/or give to collector).

2.5. Estimation of the fraction of population burning MSW

During transect walk, the total number of waste piles and burning incidence along the study routes were identified and noted down. Simultaneously, household surveys were conducted to know the status of total population residing in waste piles burning route and whether they were participating to the waste collection

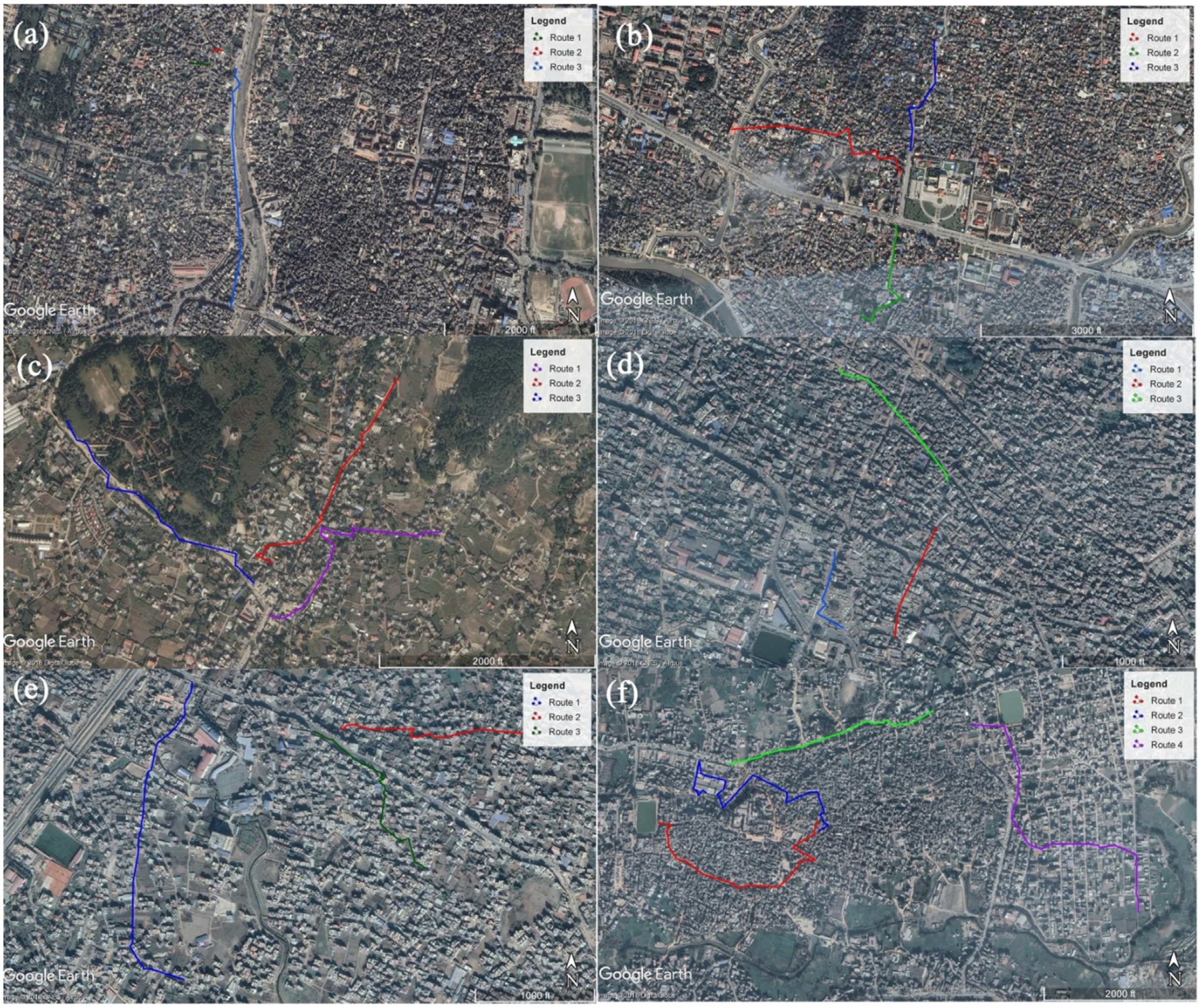

Fig. 2. Study routes. (a) Kalimati/Dallu (urban core); (b) Baneshwor (urban core); (c) Budanilkantha (sub-urban); (d) Lagankhel (urban core); (e) Mahalaxmi/Gwarko (sub-urban); (f) Bhaktapur (urban core and sub-urban).

services. Those who were not participating to waste collection services, the information of their methods of waste management practices (e.g., bury, burning, and composting) were obtained while interviewing. The household perception data of waste burning was then tabulated. Fraction of population burning MSW (P_{frac}) was estimated, which the ratio is of population who is not participating at waste collection to population whose waste is collected for disposal or landfilling (IPCC, 2006). From the above statement, population who was not participating at waste collection services is assumed to burn their waste. The P_{frac} was correlated with observation-based waste piles burning incidence through transect walk (i.e., waste piles burning per household).

2.6. Estimation of the fraction of MSW burning at disposal sites

To know the status of waste that was really dumped or burnt in the disposal site (λ), waste collection vehicles were tracked from waste collection points to disposal points in all the study routes. Study team visited to each waste collection points before 5:00 in the morning. To track the vehicles, motorbikes were used. Before heading to this study, different stakeholders (i.e., Department of Environment, KMC, Teku; Department of Environment, LSMC, Balkumari; Bhaktapur municipality; and locals) were consulted about the waste collection vehicle types, time, routes, frequency of collection, and availability of drivers. After the vehicles have been followed, visual inspection was made thoroughly at the disposal sites to check whether there were any signs of MSW open burning practices. Moreover, digital photographs were taken for visual estimation in the data analysis later.

2.7. Municipal solid waste generation

The series of study on MSWGR are not conducted in the municipality level in Nepal. The most widely used studies are reported to be SWMTSC (2015), ADB (2013), Dangi et al. (2011), SWMRMC (2008), Alam et al. (2008), and Nippon Koei Co. Ltd. and Yachiyo Engineering Co. Ltd. (2005). For this study, ADB (2013) and SWMTSC (2015) were considered because those are the latest studies and contain information of all municipalities which were studied.

2.8. Emission estimation method

The emissions from MSW open burning of valley municipalities were calculated. To calculate MSW burned at source and disposal sites of the urban and sub-urban neighborhood of valley municipalities, guidelines from different literatures were used (e.g., Shrestha et al., 2013a,b; IPCC, 2006; Shrestha, 2014).

2.8.1. Solid waste open burning at source

$$M_s = Pc \times MSWGR \times \delta \times P_{frac} \times \eta \times 365 \quad (2)$$

where M_s is the amount of open-burned MSW (kg/year); Pc is population (capita); MSWGR is per capita MSW generation rate (kcd); δ is fraction of combustible MSW; P_{frac} is fraction of population burning waste; and η is burning/oxidation efficiency (fraction), which is 0.4 (compiled by Shrestha, 2014).

2.8.2. Solid waste open burning at disposal site

$$M_s = Pc \times MSWGR \times \varepsilon \times \lambda \times \delta \times \eta \times 365 \quad (3)$$

where M_s is amount of open-burned MSW (kg/yr); Pc is population (capita); MSWGR is per capita MSW generation rate (kcd); ε is MSW collection efficiency (fraction that is disposed/land filled); λ is fraction of the waste that is actually burned relative to the total amount of waste disposed at a disposal site; δ is fraction of combustible MSW, and η is burning/oxidation efficiency (fraction).

2.8.3. Emissions

The total emission from MSW open burning can be estimated by multiplying activity data with emission factors (Shrestha et al., 2013a,b; IPCC, 2006; Shrestha, 2014; Defra, 2009). Generally, emission factor is expressed as grams of pollutant emitted per kilogram of fuel burned. The activity data (e.g., MSW generations) are the baseline for the emission estimation. The emissions for valley municipalities were estimated using equation (4) as reported by the above literatures.

$$Em_i = M_s \times EF_i \quad (4)$$

where Em_i is emission of pollutant i; EF_i is emission factor of pollutant i; M_s is amount of MSW burned.

The emission factors (EFs) presented in this paper is obtained from various literatures (i.e., country's specific as well as global based measurement). For estimating the mass of MSW open burning, EFs for CO, CO_2, NO_x, BC, $PM_{2.5}$, CH_4, OC, NH_3, and EC were obtained from the recently on-field measurements during NAMASTE campaign in Nepal (Stockwell et al., 2016; Jayarathne et al., 2018). Because of lack of country specific EFs for SO_2, global EF was considered which is a laboratory based measurement (Akagi et al., 2011). Moreover, EFs for PM_{10} and NMVOC were selected which is also a global based measurement (USEPA, 1995).

2.9. Data analysis and presentation

The computational tool such as MS-Excel was used to compile and analyse the data, whereas, R-Studio and Google earth were used to present the results. R-Studio is free and open-source software, which is used for data analysis, developing various graphics and modelling the findings in the field of environment, ecology, soil science and other scientific disciplines. In this study, R-studio is used for outlining per capita waste burnt accordingly geographic location of each study sites. Moreover, Google earth is used for delineating study routes and waste burning points. Arc-GIS is also used for presenting the study map.

3. Results and discussion

3.1. Population demography

The numbers of households counted along the study routes are shown in Table 3. Their population is determined using the average household size calculated from the survey results. The data of urban population for 2011 and projected population for 2016 for Nepal were 4,523,821 and 5,552,712 respectively (CBS, 2014a,b). The total population of 2011 for KMC, LSMC, Kirtipur, Bhakatapur and Madhyapur Thimi was 1,426,641 (CBS, 2012). Based on the above information, the projected population for 2016 for valley municipalities is estimated to be 1,751,114.

3.2. Waste combustible fraction

The waste combustible fraction was determined experimentally (see Section 2.2). Values ranged from 0.53 to 0.66 with an average of 0.57 (Fig. 3). From visual inspection, the waste piles were estimated to be 50% organic, 30% plastic, 10% paper, 3% rubbers, 2% metals, 2% textile, 1% glass and 2% other material. Moreover, sample organic waste piles were wet, whereas rest fractions were dry. Waste combustible fraction experiment was carried out immediately after rain disappeared. Thus, the results were based on all the aforementioned factors.

The experimental value presents the real-world emission parameter of Kathmandu valley municipalities, which is not adopted by any national study yet. As a pilot study, the experiment was limited to one site and five samples. As all five municipalities lie together which shares the same geographic boundary and similar socio-economic activities, lifestyles and climatic condition, the waste composition of each municipality is not expected to vary greatly. Therefore, it is reasonable to assume that the average waste combustible fraction value (0.57) determined in Kirtipur can be applied to all valley municipalities.

3.3. Estimation of the fraction of population burning MSW

To calculate MSW open burning emissions, fraction of population burning MSW is fundamental. The P_{frac} was calculated for

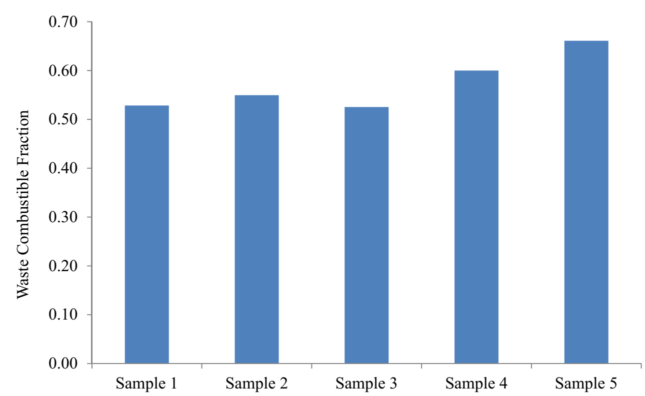

Fig. 3. Waste combustible fraction based on field experiment, 2016.

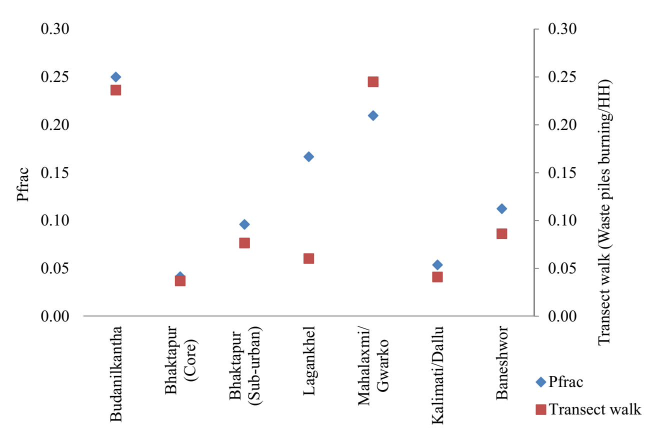

Fig. 4. Pfrac with respect to transect observation.

the valley municipalities referring the survey data. Of 179 households sampled, the average value of P_{frac} was 0.13 (Table 3). P_{frac} for Budanilkantha was comparatively higher than any other neighborhood. This could be due to irregular waste collection services because of less accessible, narrow and sloped roads to reach many of these homes. Higher value of P_{frac} infers higher waste burning or low waste collection efficiency in the neighborhoods. To validate P_{frac} with transect walk (i.e., waste piles burning per household), coefficient of correlation was calculated which is 0.88. P_{frac} has a strong correlation with MSW open burning along the transect line (Fig. 4). To some extent Lagankhel has a distinct case. In Lagankhel, some people burn waste in front of their houses and some burn at the nearest temporary informal dumping site (e.g., Lagankhel Bus Park). This could be the reason P_{frac} and MSW open burning incidence (e.g., waste piles burning per household) along transect of Lagankhel are feebly allied and coefficient of correlation to not exceed 0.88.

3.4. Estimation of the fraction of MSW open burning at disposal sites

All the waste that was collected through vehicles was tracked up to the final transfer station and disposal sites. The observations

Table 1
Total number of waste piles at the study routes.

Study routes	R1	R2	R3	R4	Total
Budanilkantha	19	20	21	–	60
Bhaktapur (core)	30	29	–	–	59
Bhaktapur (sub-urban)	–	–	25	24	49
Lagankhel	13	4	8	–	25
Mahalaxmi/Gwarko	28	21	24	–	73
Kalimati/Dallu	3	2	15	–	20
Baneshwor	11	11	11	–	33
Total					319

Table 2
Fraction of MSW open burning.

Study routes	Total no. of waste piles	No. of waste piles burning incidence	No. of waste piles non-burning incidence	Waste piles burning incidence (%)	Waste piles non-burning incidence (%)
Budanilkantha	60	39	21	65.00	35.00
Bhaktapur (core)	59	4	55	6.780	93.220
Bhaktapur (sub-urban)	49	17	32	34.69	65.31
Lagankhel	25	7	18	28.00	72.00
Mahalaxmi/Gwarko	73	49	24	67.12	32.88
Kalimati/Dallu	20	6	14	30.00	70.00
Baneshwor	33	15	18	45.45	54.55
In overall	319	137	182	42.95	57.05

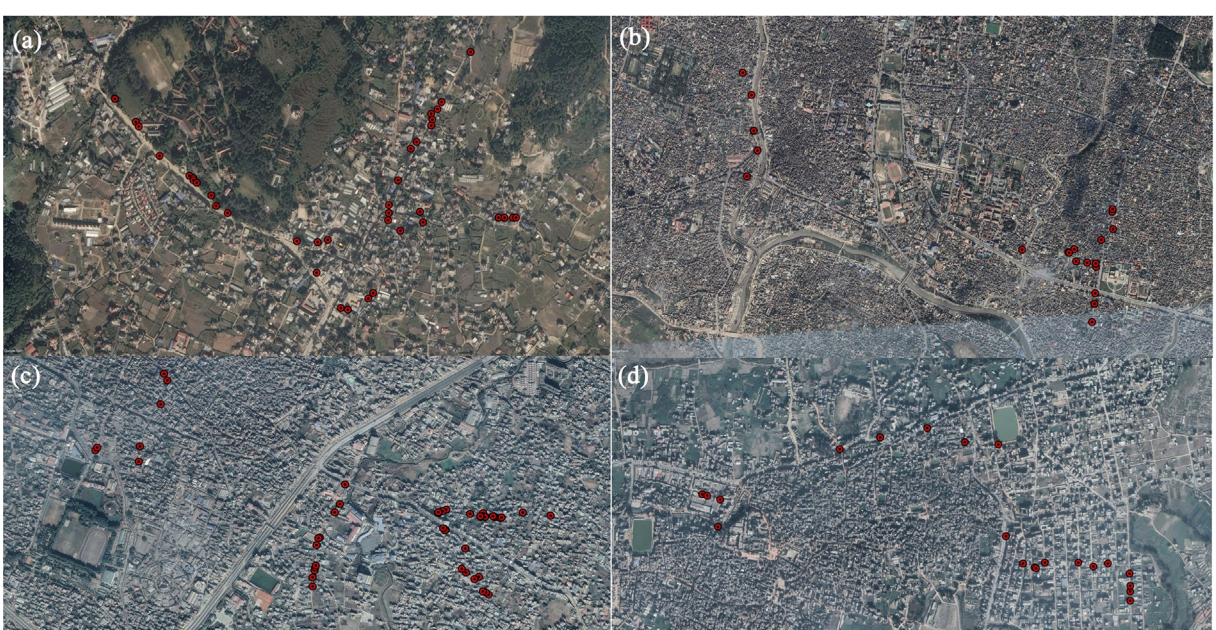

Fig. 5. Waste burning points at the study routes. (a) Budanilkantha (sub-urban); (b) Dallu/Kalimati (urban core) and Baneshwor (urban core) of KMC; (c) Mahalaxmi/Gwarko (sub-urban) and Lagankhel (urban core) of LSMC; (d) Bhaktapur (sub-urban and urban core).

have been made for each selected informal dumping site. The burning practices have not been identified in the disposal sites. The fraction of MSW-burned at the dumping sites is assumed as zero.

3.5. MSW open burning and emissions

Of 319 waste piles that have been identified (Tables 1 and 2), 137 (i.e., 43%) waste piles were found to be actively burning in different routes of the urban and sub-urban area (Fig. 5) of Kathmandu valley. Along transect of 1131 households study, the total mass of waste pile burnt is estimated to be 72 kg/day (Table 3). The highest waste burning was prevailing in Budanilkantha (0.027 kcd) followed by Mahalaxmi/Gwarko (0.017 kcd), Lagankhel (0.014 kcd), Baneshwor (0.012 kcd), Bhaktapur sub-urban (0.008 kcd), Kalimati/Dallu (0.006 kcd), and Bhaktapur core (0.003 kcd) (Fig. 6).

The household survey of Budanilkantha depicts a waste collection frequency to be very low (e.g., three times a week to twice a month). In contrast, Kalimati/Dallu and Baneshwor, which are the municipality core of KMC have low per capita waste burning because of higher waste collection efficiency (i.e., 86.9%), reported by ADB (2013). Mahalaxmi/Gwarko which is another sub-urban of LSMC has higher per capita waste burning and P_{frac} for the similar reason. The waste collection frequency as per survey is one to three times a week. In contrast, Lagankhel (i.e., municipality core of LSMC) has comparatively lower per capita waste burning, which closely relates with high waste collection efficiency (71.2%), reported by ADB (2013) and based on the survey (i.e., seven days a week). As compared to sub-urban neighborhoods, Bhaktapur core has lower per capita waste burning. This could be due to higher waste collection efficiency (i.e., 86.5%), reported by ADB (2013). To know the status of waste that was really dumped or burnt in the dumping site, vehicles were tracked by surveyors followed by visual inspection and digital photographs. In this way, the fraction of MSW burned at the disposal sites were determined as zero.

The total mass of MSW burned during 2016 for valley municipalities is estimated to be 7400 tons (i.e. 20 tons/day), which was of 3% of the total waste generated in that year. This result is compared with similar south Asian cities as well as other developing and developed countries. The mass of MSW burned is higher than other developed countries. European Union and United States determined MSW open burning rates around large cities, which are in between 0.25% and 0.3% of the total MSWGR (Park et al., 2013). The MSW burning of valley municipalities is 131,377, 197, 48, 11, 5, and 4 folds lower than global estimates, Mexico City, Mumbai, Delhi and Agra, Kanpur, and Ulaanbaatar respectively (Table 4). In Mexico City, MSW open burning is high (i.e., >50%)

Table 3
Summary of MSW open burning in the Kathmandu valley.

Study routes	Total no. of HHs around waste piles area	Avg. HH population size	Total no. of family members around waste piles area	Total weight of the trash that burnt (kg/day)	Daily per capita MSWGR (kg/capita/day)	Total daily MSW generation (kg/day)	P_{frac}	Waste burning (kg/capita/day)
Budanilkantha	165	4.86	801	21.86	0.48	383.15	0.25	0.027
Bhaktapur (core)	108	6.30	681	2.22	0.35	235.17	0.04	0.003
Bhaktapur (sub-urban)	222	5.43	1207	9.13	0.35	416.73	0.10	0.008
Lagankhel	116	4.50	522	7.38	0.37	194.09	0.17	0.014
Mahalaxmi/Gwarko	200	4.96	992	16.94	0.36	354.04	0.21	0.017
Kalimati/Dallu	146	5.14	750	4.27	0.46	348.52	0.05	0.006
Baneshwor	174	5.09	885	10.54	0.46	411.14	0.11	0.012
In overall	1131	5.16	5838	72.36	0.40	2342.85	0.13	0.012

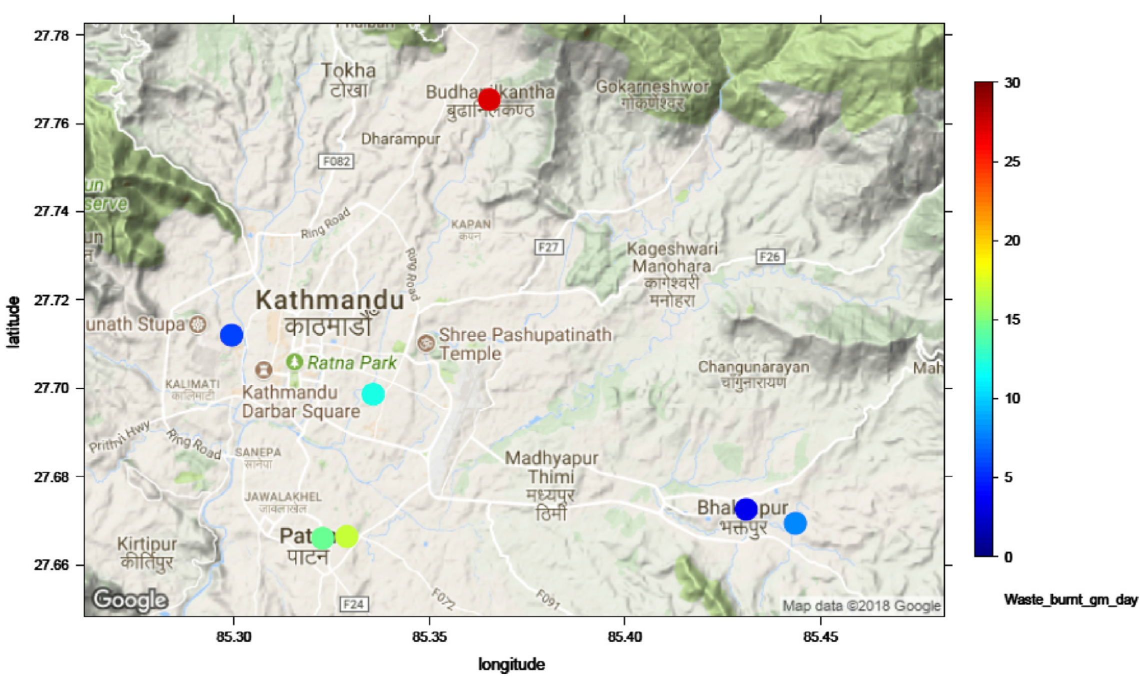

Fig. 6. Per capita waste burning (gm/capita/day) at the study sites.

Table 4
Comparative estimates of MSW open burning from global perspective.

Places	Waste burning (in Gg)
Kathmandu valley municipalities (2016)[a]	7.4
Delhi (2015)[b]	79.6
Agra (2015)[b]	81.4
Kanpur (2005)[c]	35.0
Mumbai (2005)[d]	352.6
Ulaanbaatar (2005)[e]	31.5
Mexico City (2006)[f]	1460.0
World (2014)[g]	972,190

MSW open burning percentage for 2005 is assumed same as that of 2007 for Kanpur.
[a] Estimation from this study.
[b] Nagpure et al. (2015).
[c] Calculated (MSW open burning percentage as of 2007 from Sharma, 2010; population as of 2005 from United Nations, 2012; MSWGR as of 2004/05 from CPCB, 2017).
[d] Calculated (MSW open burning percentage as of 2005 from Sharma, 2010; population as of 2005 from United Nations, 2012; MSWGR as of 2004/05 from CPCB, 2017).
[e] Calculated (MSW open burning percentage as of 2005 from Guttikunda, 2007; population as of 2005 from United Nations, 2012; MSWGR as of 2005, avg of summer and winter from JICA, 2007).
[f] Hodzic et al. (2012).
[g] Wiedinmyer et al. (2014).

in the poorest area (Hodzic et al., 2012). The global waste burning status is presented by Bond et al. (2004). According to it, Asia contributes 14 Tg/year, Africa (5 Tg/year) and global (33 Tg/year). This result is inconsistent with Wiedinmyer et al. (2014) which states MSW open burning to be 972 Tg/year after summing-up residential and dump sites burning. The waste burning varies from places and occurs due to variety of reasons. It is more frequent where waste collection services are sparse, expensive, and unavailable (Wiedinmyer et al., 2014). Small and medium level cities, and cities without landfill facilities and with no or partially waste collection service causes more MSW open burning (Guttikunda et al., 2014). Other reasons are lack of adequate waste collection services (Ramaswami et al., 2016) as well as irregular waste collection services, inept disposal methods, and poor attitude of dump-burn practices which lead to MSW open burning in residential and open spaces. Moreover, proper waste recycling systems are also trifling in the country. In average, the waste collection frequency in the Kathmandu valley is three times a week (SWMTSC, 2015).

This study estimates the total emissions from MSW open burning to be $PM_{2.5}$ 55 tons (OC 42 tons and EC 1.4 tons), PM_{10} 60 tons, BC 25 tons, CO_2 11,900 tons, CH_4 30 tons, SO_2 5.0 tons, NO_x 19.2 tons, CO 630 tons, NMVOC 112 tons, and NH_3 5.7 tons per year (Fig. 7). The results have been compared with existing estimates from Diesel Generator (DG) sets, vehicle traffic, and manufacturing industries of different years to establish MSW burning as a leading in the valley. World Bank (2014) reported DG sets emission for Kathmandu valley for 2012/2013. The estimates of SO_2, NO_x, CO, PM_{10}, BC, OC and CO_2 from MSW open burning are 11, 281, 2, 6, 9, 3, 18 folds lower than DG sets emissions respectively. Comparing waste burning emission with vehicular emission, NO_x is 834 folds lower, CO is 49 folds lower, BC is 86 folds lower and CO_2 is 130 folds lower than reported by Shrestha et al. (2013a,b). Comparing with manufacturing industries (Pradhan et al., 2012), MSW open burning emits SO_2 and NO_x which are 607 and 44 folds lower respectively. However, CO and NMVOC are 1.6 fold and 2 folds higher respectively than manufacturing industries (Table 5).

Moreover, emissions from this study are compared with other regional and international findings. The emissions such as SO_2, NO_x, CO, PM_{10}, and $PM_{2.5}$ resulted from trash burning from valley municipalities are 80, 104, 44, 128 and 97 folds lower than Delhi respectively. Similarly, SO_2, NO_x, CO, and NH_3 are 146, 209, 96

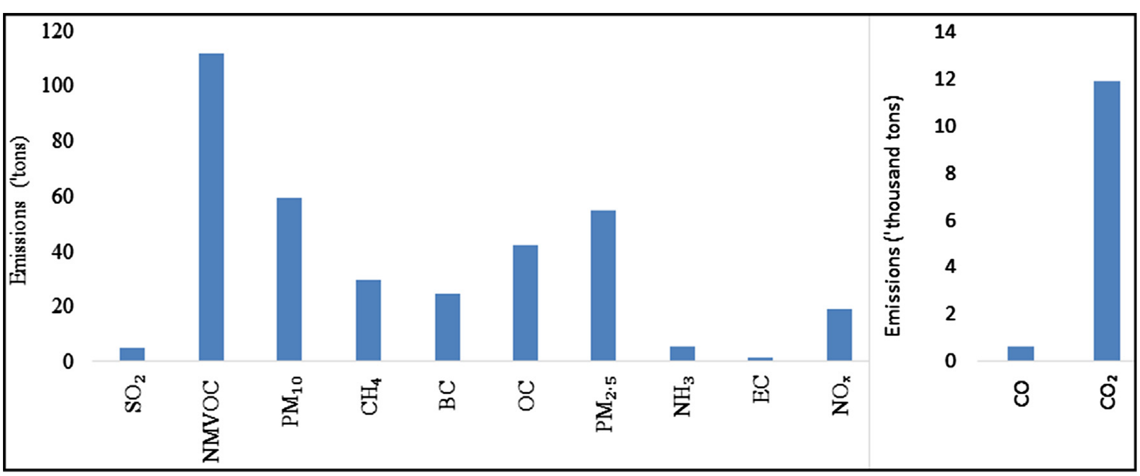

Fig. 7. Emissions from MSW open burning, valley municipalities.

Table 5
Comparative estimates of emissions from different sources in the Kathmandu valley.

Emission sources	SO_2	NO_x	CO	NMVOC	PM_{10}	CH_4	BC	OC	CO_2	$PM_{2.5}$	NH_3	EC
Solid waste burning – Kathmandu valley municipalities (2016)[a]	5	19.2	629.9	111.5	59.5	29.5	24.5	42.2	11,913	54.8	5.7	1.4
DG sets – Kathmandu valley (2012/13)[b]	54	5400	1200	–	380	–	221	120	210,150	–	–	–
Vehicular emission – Kathmandu valley (2010)[c]	–	16,000	31,000	–	–	–	2100	–	1,554,000	–	–	–
Manufacturing industries – Kathmandu valley (2012)[d]	3014	838	389	53	–	–	–	–	–	–	–	–

[a] The estimation from this study.
[b] World Bank (2014).
[c] Shrestha et al. (2013a,b).
[d] Pradhan et al. (2012).

Table 6
Comparative estimates of emissions (in Giga grams) from global perspective.

Emission sources	SO_2	NO_x	CO	NMVOC	PM_{10}	CH_4	BC	OC	CO_2	$PM_{2.5}$	NH_3	EC
Kathmandu valley municipalities (2016)[a]	0.01	0.02	0.63	0.11	0.06	0.03	0.02	0.04	11.91	0.05	0.01	0.00
Delhi (2010)[b]	0.40	2.00	27.80	–	7.60	–	–	–	–	5.30	–	–
Mexico city (2012)[c]	0.73	4.02	60.59	–	–	–	–	–	–	–	1.46	–
Ulaanbaatar (2006)[d]	–	–	–	–	4.07	–	–	–	–	3.05	–	–
World (2014)[e]	486	3636	36,943	–	11,569	3597	632	5123	1,412,592	9527	1089	–

[a] The estimation from this study.
[b] Guttikunda and Calori (2013).
[c] Hodzic et al. (2012).
[d] Guttikunda (2007).
[e] Wiedinmyer et al. (2014).

and 256 folds lower than Mexico City respectively. Furthermore, PM_{10} and $PM_{2.5}$ are 68 and 56 folds lower than Ulaanbaatar respectively. Likewise, SO_2, NO_x, CO, PM_{10}, CH_4, BC, OC, CO_2, $PM_{2.5}$ and NH_3 are 97,219, 189,375, 58,649, 194,438, 121,936, 25,793, 121,409, 118,576, 173,859, and 191,027 folds lower than global estimates respectively (Table 6). Some other study shows that MSW burning contributes direct PM emissions, approximately 8% in India, 22% in China, 33% in Bangladesh, and 69% in Pakistan (Wiedinmyer et al., 2014). In Mumbai, waste burning and landfill fires emit 22,000 tons per year of air pollution in the form of PM, HC, CO, NO_x, and SO_2 including dioxins/furans (10,000 TEQ grams annually) (Annepu, 2012). These emission can lead to severe health impact like acute and chronic respiratory disease, heart diseases, and allergic hypersensitivity (McDonnell et al., 2000) including impacts on local climate because BC and CO_2 having a high global warming potential.

4. Conclusion

In Nepal, this study for the first time attempted to estimate real-world emission parameters, which have been used for estimating MSW open burning. Moreover, it also accounts daily waste burning incidence in the Kathmandu valley. This study presents a clear picture that more MSW open burning prevails at the sub-urban neighborhoods than the municipality core. This is due to lower waste collection frequency (or efficiency) at sub-urban area than the municipality core. P_{frac} has strong linkage with waste collection efficiency. Higher the waste collection efficiency, lower will be P_{frac} and vice versa. This study reveals that open burning practices are not performed in the municipal designated disposal site.

The method applied in this study can be also replicated to more neighboring cities of the developing countries to obtain amount of pollutants from MSW open burning. For the cities of developing countries, which waste composition and climatic condition are similar to valley municipalities, the value of emission parameters can be adopted. As MSW open burning study is very primitive in Nepal, more research and development are indispensable. Moreover, site specific waste combustible fraction experiment is recommended for future research work.

Although Government of Nepal enforced SWM act 2011 for better SWM practices, it has not achieved satisfactory result yet. Thus, the result of this study is likely to become a stronger foundation for SWM policies that valley municipalities including other urban areas can implement in the immediate future. Amending the act and incorporating the most effective MSW open burning control strategy (e.g., increasing waste collection services, improved waste segregation at the source, improved waste collection systems, banning MSW open burning in the community level, high penalty charge for use-throw practices, extending more Kawadi centres for waste recycling, systematic waste disposal practices, air curtain incineration practices, and awareness) are the foremost steps to reduce this pollution and its effects.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.08.013.

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