Air pollution exposure and health impacts in the Kathmandu valley

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Abstract: Air pollution monitoring in Kathmandu valley during 2003–2007, 2014–2015 and 2017 onwards shows that there has been substantial decrease in particulate air pollution with around 50% reduction in overall average PM_{10} from 123 $\mu g/m^3$ for the period 2003–2007 to 61$\mu g/m^3$ during 2018–2020 equivalent to around 3.2% decrease per year from 2003 to 2020. Similarly, a reduction of 13.6% in $PM_{2.5}$ from 49 $\mu g/m^3$ during 2014/15 to 42.4 $\mu g/m^3$ during 2017–2020 was found with around 4.2% decrease per year from 2014–2015 to 2020. However, the averages are still 3–4 times higher than WHO 2005 guideline values and pose serious threats to the valley inhabitants. Assessment of respiratory health burdens like chronic obstructive pulmonary disease and acute respiratory infection including pneumonia showed 6%-13% of the respiratory morbidities can be attributed to $PM_{2.5}$ in Kathmandu valley. Under 35% $PM_{2.5}$ reduction scenario in 2030, the expected avoidable fractions are found to be 2.5–4.9%.

Keywords: ambient air pollution; attributable burden; avoidable burden; health effects; Kathmandu valley; ozone; particulate matter.

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1 Introduction

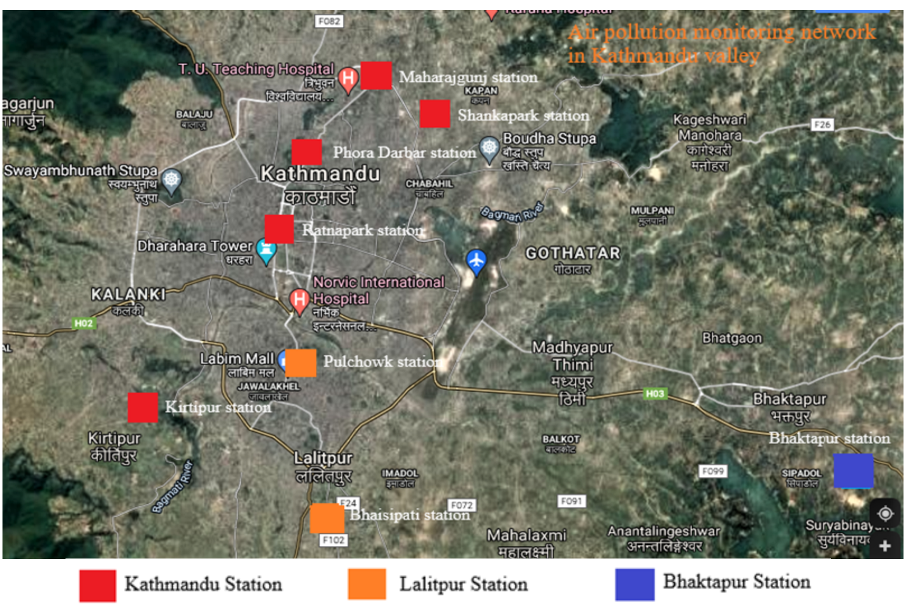
Air pollution is one of the major environmental problems in the world today with 4.2 million deaths per year attributed to ambient air pollution, and 91% of world population lives in places exceeding WHO 2005 air quality guidelines. According to 2016 WHO estimates, 58% of ambient air pollution-related premature deaths were due to ischemic heart disease (IHD) and strokes, 18% of deaths were due to chronic obstructive pulmonary disease (COPD) and acute lower respiratory infection (ALRI), and 6% of deaths were due to lung cancer (WHO, 2018). In addition to ambient air pollution, indoor smoke from household air pollution is also a serious global health risk for 3 billion people who are cooking and heating homes with biomass fuels and coal. WHO reports that 3.8 million premature deaths were attributable to household air pollution in 2016. Close to half of deaths due to pneumonia among children under 5 years of age are caused by particulate matter inhaled from household air pollution (WHO, 2020). Among these 3.8 million deaths due to household air pollution, studies showed that 27% are due to pneumonia, 8% from stroke, 27% from IHD, 20% from COPD and 8% from lung cancer (WHO, 2020). Almost all of the burden was and is in low-to-middle-income countries. Lung cancer has been found to be associated with household air pollution along with other risk factors and air pollution might be considered as the major risk factor of lung cancer in Kathmandu valley (Subedi et al., 2018). Chronic exposure of poor air quality increases the chance of non-communicable diseases (NCD) such as lung diseases, heart diseases and cancers (Saud and Paudel, 2018). The study revealed the current scenario of Kathmandu's air quality status and its impact on human health along with review on legislative and future action plan and areas to be addressed concerning air pollution and public health. Nepal is an example of a country where the levels of air pollution have been and are high particularly in its capital Kathmandu.

The major sources and contributing factors of air pollution in Kathmandu valley have been identified as fossil fuel combustion mainly due to vehicles, brick kilns, household cooking, industrial emissions, resuspension of dust particles in roads, rapid urbanisation and overpopulation. A recent study conducted in 2017 by the Department of Environment (DoEnv) of the Government of Nepal (GoN) reported that major sources of air pollution assessed by PM_{10} emission in Kathmandu valley are transportation (30%), construction (53%), brick kiln (9%), domestic cooking (5.4%), and other sources, including industries, waste burning and agriculture (2.6%) (DoEnv, 2017). Similarly, a study in 2016 by the Nepal Health Research Council (NHRC) reported that vehicular emissions constitute about 38% of the total pollution in Kathmandu valley alone which is slightly different from the DoEnv study. Furthermore, it has been reported that the transportation sector could be responsible for 63% of particulate matter (PM) in the valley (NHRC, 2016). When the rate of vehicle registration in Nepal is examined over the past 30 years, then it is found that the annual number of registrations have increased many folds. Since the year 2000, registrations have grown by an order of magnitude from 41 thousand (2000/2001) to over 440 thousand registrations per year during 2017/2018 fiscal year (Department of Transport, 2020) Brick kiln emission is another major source of air pollution in Kathmandu valley. It was reported in 2017 that the average coal consumption in Kathmandu was around 56,100 tons/year and other local fuels 330 tons/year. Within the valley, the brick production sector has become the single largest consumer of coal. The share of energy in the total cost of brick production is 30% to 40%. Despite the importance of the brick sector, about 96 percent of kilns are still traditional types and use energy-intensive and highly polluting technologies. This causes harmful impacts on human health mainly from particulate matter. Most operating brick kilns in Nepal are highly polluting since they use crude technology and low-quality coal for fuel (DoEnv, 2017). Last but not the least, according to population census 2011, around 11.8% of households in Kathmandu still use unprocessed biomass fuels though the percentage is much lower compared to national percentage use of unprocessed biomass fuel in Nepal. Additional information on WHO estimates are provided in the Supplementary Material of this paper.

The Nepal Ambient Monitoring and Source Testing Experiment (NAMaSTE) field campaigns in 2015 and 2018 focused on measuring emission factors from several types of brick kilns, open burning of garbage, generators powered by diesel and petrol, various wood- and dung-fuelled cook stoves and cooking and heating fires, crop residue burning, and serviced and un-serviced motorcycles (Jayarathne et al., 2018; Stockwell et al., 2016). The campaign also led to a source apportionment of $PM_{2.5}$ and PM_{10} as well as a modelling study that looked at the implications for ambient air pollution of emissions factors for vehicles and brick kilns. The NAMaSTE source apportionment study found that anthropogenic combustion sources (including biomass burning, garbage burning and fossil-fuel combustion) were the greatest contributors of $PM_{2.5}$. The modelling study found that the older emissions inventory was underestimating the emission of particulates by vehicles in the Kathmandu valley by more than a factor of 100. While the NAMaSTE campaign estimated emissions from diesel driven water pumps, a more recent ICIMOD study used a relatively larger sample size to estimate more reliable emissions factors (Adhikari et al., 2019).

In addition to the major sources of air pollution, topography of Kathmandu valley is also considered as a contributing factor to air pollution. In order to check the air pollution levels in the ambient air in Kathmandu valley, the Ministry of Population and Environment (MOPE) installed 6 fixed stations at different places within the valley covering traffic areas (Thamel & Putalisadak), traffic plus residential areas (Lalitpur & Bhaktapur) and background areas (Matsyagaon & Kirtipour). PM_{10} was monitored continuously for several years starting from 2002 till 2007. The results showed that Kathmandu's air was highly polluted with annual average 6–7 times higher than the WHO 2005 guideline for PM_{10} though the annual average showed marginally declining trend during the period (ICIMOD, 2020). Thereafter, even though there have been many occasional monitoring studies in the valley, the non-stop monitoring of air pollutants with $PM_{2.5}$, CO and NO_2 throughout the year was conducted by NHRC in 2014–2015. Three fixed stations were installed, one each in the three districts of the valley covering high traffic area (Putalisadak), medium traffic area (Mahalaxmisthan near Pulchowk) and relatively low traffic area (Siddhi Memorial Hospital, Bhaktapur). Results again showed that the air pollution levels were many-folds higher than WHO 2005 guidelines, specifically regarding $PM_{2.5}$ and NO_2 (NHRC, 2016).

Figure 1 Air pollution monitoring network in Kathmandu valley (see online version for colours)



The monitoring of air pollutants in Nepal started with coverage of many urban areas of Nepal outside Kathmandu valley mainly through DoEnv, Ministry of Forests and Environment from 2016 onwards. The monitoring is currently ongoing within the valley and also in all provincial states of Nepal with dozens of monitoring stations installed outside the valley as well. The present study is conducted to assess the air pollution situation in Kathmandu valley based upon the latest available air pollution monitoring data of particulate air pollution by DoEnv and US Embassy stations since 2017 and Ozone level monitored by US Embassy stations in Kathmandu. The study area of air pollution network installed by DoEnv and US Embassy in Kathmandu valley is shown in the Figure 1. Monitoring stations are spread across different types areas such as high traffic urban core areas (Ratnapark, US Embassy installed stations, Phora Darbar and Maharajgunj), moderate traffic urban areas (Shankapark, Pulchowk and Bhaisiptai), and urban background and low traffic areas (Kirtipur and Bhaktapur). Health effects are assessed based upon the recent data on air pollution level and health burden along with health effect coefficients estimated by studies on Kathmandu valley and meta-analysis.

This paper reviews the knowledge on air pollution and its health impacts in Kathmandu, and some scenarios are run in order to assess the potential benefits of policies that reduce air pollution. In particular, diurnal, daily and monthly variations and annual trends of $PM_{2.5}$ and O_3 are analysed, and health risk assessment of $PM_{2.5}$ is estimated. A detailed analysis of the brick kilns sector is also carried out. Additionally, data related to the Covid-19 lockdown during Spring and Summer 2020 was analysed.

2 Methodology

The analysis is based upon available air pollution monitoring data and health data along with health effect estimates obtained by studies conducted in Kathmandu valley. Details are described as follows.

2.1 Air pollution data

Air pollution data monitored by MOPE, DoEnv, Ministry of Forests and Environment and US Embassy are obtained for Kathmandu valley from the following sources.

- Daily PM_{10} levels were compiled for the years 2003–2007 from ICIMOD (ICIMOD, 2020).
- Daily PM_{10} and $PM_{2.5}$ data for the years 2017–2020 (Till August, 2020; some hourly data also available for 2016) were obtained and compiled from Data Platform of the World Air Quality project, https://aqicn.org/city/kathmandu/ (The World Air Quality Project, 2020).
- Additionally, $PM_{2.5}$ and Ozone data were compiled from US embassy website, https://www.airnow.gov/international/us-embassies-and-consulates/ (US Embassies and Consulates, 2020).
- Estimates of NHRC study of air pollution in Kathmandu valley, 2014/15 was used.
- Data have been collected on hourly and daily basis for the parameters.
- Altogether seven stations within Kathmandu valley namely Ratnapark, Shankapark, US Embassy (Maharajgunj), Phora Darbar, Bhaisipati, Pulchowk and Bhaktapur were used for analysis. Data for Kirtipur station was unavailable.

2.2 Health burden data

Available total annual health burden data on respiratory diseases was collected from the Department of Health Services (DoHS) Annual Report, 2016/17. The main respiratory diseases covered COPD and ARI including pneumonia (DoHS, 2016/17).

2.3 Analysis of data

Analysis of the available air pollution data is accomplished to assess the status of air pollution in Kathmandu valley and its trends based upon raw concentrations. Analysis was done through annual, monthly, daily and hourly variations of the available air pollution data. Trend analysis was done to examine the difference in air pollution situation from 2003–2007, to 2014/15 and 2017-August 2020. Mean and median concentrations including population weighted averages were computed for the assessment. For daily pollution level assessment, frequency tables were constructed with respect to observations above WHO 2005 guidelines. Assessment of health impacts with computation of attributable fraction (AF), attributable burden and avoidable burden is based upon health effect coefficients obtained for Kathmandu valley from previous studies and current frequency distribution of ambient air pollution levels. Attributable health burdens are calculated with total burden of disease obtained from DoHS annual report. Additionally, avoidable burdens are also calculated for the assessment of avoidable burdens in alternate hypothesised but improved scenarios such as business as usual (BAU) and progressive scenarios in 2030 compared to the baseline scenario (2017–2020) since input data for baseline information is available for 2017–2020 period. Mathematical expression for estimating AF is provided in the Supplementary Material. The avoidable fraction and avoidable burden are calculated as:

$$\text{Avoidable fraction} = AF_{\text{Baseline scenario}} - AF_{\text{Alternate scenario}} \text{ and Avoidable burden} = \text{Avoidable Fraction} \times \text{Total Burden}$$

3 Results

3.1 Air pollution monitoring network

Currently, air pollution monitoring by DoEnv, Nepal Government is ongoing since 2016. Similar monitoring of air pollution is also ongoing within Kathmandu at US Embassy (Maharajgunj) and Phora Darbar by US Embassy installed stations. Altogether, there are 28 monitoring stations all over Nepal of which 8 stations are located within the Kathmandu valley. The valley air pollution monitoring network includes core areas of Kathmandu like Ratnapark, Phora Darbar, US Embassy station located at Maharajgunj and Pulchowk area of Lalitpur, relatively peripheral areas like Shankapark and Kirtipur in Kathmandu, Bhaisipati in Lalitpur and Birendra School area at Bhaktapur.

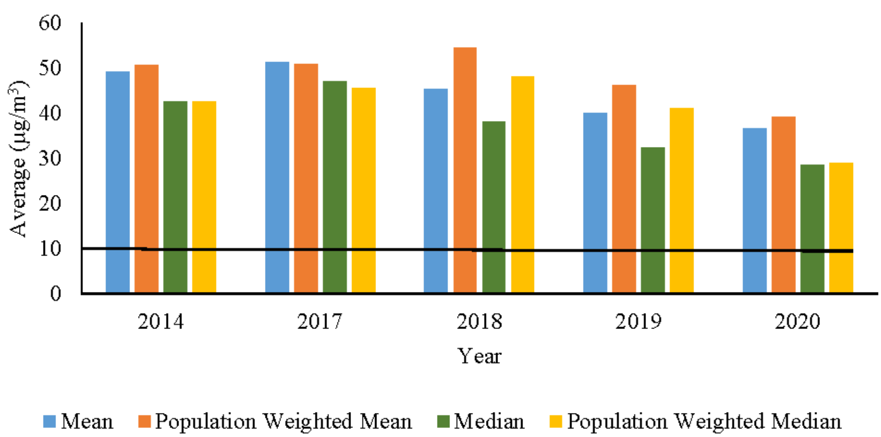
3.2 Annual trend

Annual trend analysis and assessments are done for each pollutant separately for the following time periods for which measurements were available. We have available measurements for PM_{10} for the period 2003–2007 and 2018–2020, for $PM_{2.5}$ during the period 2014/15, 2017–2020 and for O_3, 2017–2020. Before analysing in detail regarding the $PM_{2.5}$ and O_3 situation, some information from the PM_{10} trends are also useful (see Supplementary Material: Figure S1).

3.2.1 $PM_{2.5}$

Since continuous monitoring data throughout the year is unavailable for $PM_{2.5}$ in earlier phase of monitoring during 2003–2007, annual trend and corresponding comparative assessment is made from 2014/15 onwards only. The NHRC study conducted during 2014/15 showed annual average of $PM_{2.5}$ as 49 μg/m^3 which is around 5 times higher than the WHO 2005 annual guideline. The monitoring results of DoEnv and US Embassy since 2017 onwards showed substantial decrease. Compared to 2014/15, concentration levels have increased slightly in 2017. However, since then the levels have continuously decreased year after another by around 10% per year to 37 μg/m^3 which amounts to overall decrease of 24.5% since 2014/15. However, the value is still 3.7 times higher than the WHO 2005 guideline. Similarly, population weighted mean values which are slightly higher than the unweighted mean, have also decreased since 2017 consistently and reached to 38.4 μg/m^3 in 2020 (till August) which is 24.7% overall decrease. Moreover, median and corresponding population weighted median values have also decreased from 46 μg/m^3 to 29 μg/m^3 which amounts to 36.9% overall decrease considering population weighted median values (Figure 2). The decrease in $PM_{2.5}$ in 2020 (till August) is also due to the effect by COVID-19 lockdown in the valley imposed for around four and half months (data for 8 months were assessed in 2020) during when vehicle movements were minimal in the valley. Analysis showed that air pollution averages in the lockdown period in 2020 and same time period prior one year (2019) revealed that there has been a substantial decrease in air pollution levels regarding $PM_{2.5}$ air pollution with 34.6% decrease from 31.2 μg/m^3 to 20.4 μg/m^3 in the lockdown period.

Figure 2 Annual averages of $PM_{2.5}$ in Kathmandu valley (see online version for colours)

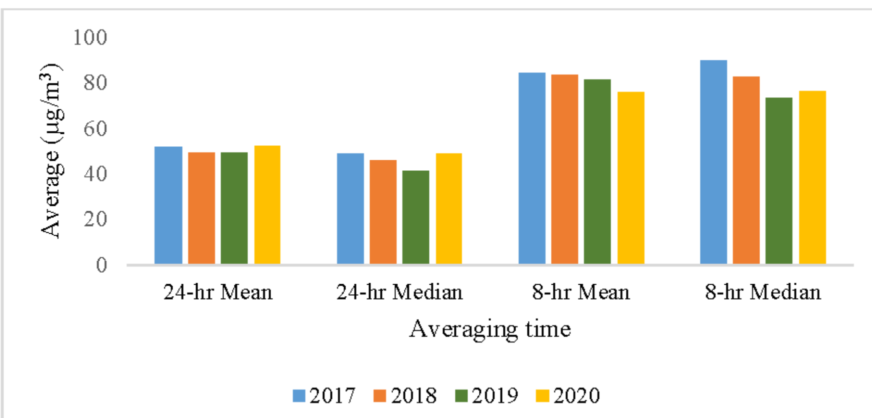


It is to be noted that the horizontal line in the figure indicates the WHO 2005 annual guideline value for $PM_{2.5}$.

3.2.2 Ozone

Data for ozone concentration measured in Kathmandu valley is only available from US Embassy monitoring via two stations installed in Kathmandu, one at Embassy itself and another in Phora Darbar which is located at the core high traffic area in Kathmandu. It is to be noted that O_3 levels are often lower near traffic areas due to titration effect of NO with O_3. Since analysis of O_3 is based upon only two stations in Kathmandu, population weighted averages are not computed for the assessment. Additionally, WHO 2005 guideline of O_3 is available for 8-hr (daily maximum 8-hr mean which is 100 μg/m^3), average is computed for 8-hr duration (10 AM to 6 PM). However, for comparative assessment, 24-hr average is also considered. Examination of annual average of O_3 shows that unlike particulate pollution, it hasn't gone down markedly since 2017 onwards. The annual 24-hr average was 51.8 μg/m^3 in 2017, went down slightly in subsequent couple of years to around 49.2 μg/m^3 but again has again risen to 52.2 μg/m^3 in 2020 (through August) with an overall average of 50.4 μg/m^3. The corresponding median averages are slightly less than the mean values again indicating positive skewness in the distribution of O_3 level. Analysis of 8-hr average showed that the annual average of O_3 has marginally lowered from 84.3 μg/m^3 in 2017 to 75.7 μg/m^3 consistently in successive years. Though comparison based upon 24-hr average showed slightly positively skewed distribution in consecutive years, analysis based upon 8-hr average showed slight positive and negative skewness in different years since 2017 (Figure 3).

Figure 3 Annual ozone concentration in Kathmandu valley (see online version for colours)



It is to be noted that conversion of ppm to μg/m^3 for O_3 is done following the conversion factors mentioned below.

$$C \text{ in mg/m}^3 = C \text{ in ppm (by volume)} \times 12.187 \times \text{molecular weight of } O_3 \quad (48)/ \; (273+25)\,^\circ \text{Centigrade}$$

$$20 \text{ ppm} = 39.4 \text{ mg/m}^3;\ 1 \text{ ppm} = 1.97 \text{ mg/m}^3 \text{ at } 25^\circ\text{C};\ 1\text{ppb} = 10^{-3} \text{ ppm};\ 1 \text{ ppb} = 1.97\,\mu\text{g/m}^3 \text{ (US EPA Standard)}$$

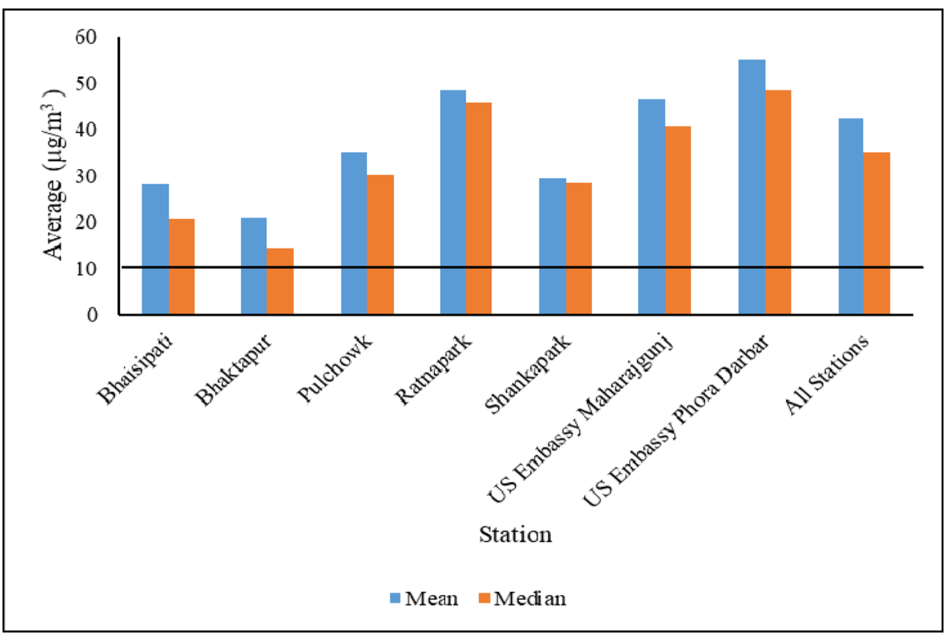
Source: https://aqicn.org/faq/2015-09-06/ozone-aqi-using-concentrations-in-milligrams-or-ppb/

3.3 Station-wise variation

Examination of station-wise variation of PM_{10} depicts highest average in Putalisadak station (213 μg/m^3) and lowest in Matsyagaon (47 μg/m^3) for the period 2003–2007 whereas during 2018-August 2020, the highest average for the period was seen in Ratnapark station (85.9 μg/m^3) and lowest in Bhaktapur station (41.8 μg/m^3). Average values in different stations depict higher values in high traffic areas compared to average traffic residential areas and lowest value in remote or background areas within the valley.

The overall station-wise $PM_{2.5}$ concentrations during 2017-August 2020 depicts highest concentrations observed at high traffic core areas of Kathmandu stations like Phora Darbar, Ratnapark and US embassy area where the averages are found to be as high as 46.5 to 55 μg/m^3. The range is alarmingly high, around 4.6–5.5 times higher than WHO 2005 annual guideline of 10 μg/m^3. Pulchowk, also a traffic area showed 35 μg/m^3. Other stations namely Bhaisipati, Shankapark and Bhaktapur stations showed lower than 30 μg/m^3 (21–29.3 μg/m^3) with the least average seen in Bhaktapur station with 21 μg/m^3 where traffic density is also significantly less than Kathmandu core areas (Figure 4). If the median values are examined, then overall median value is less than mean by 17% with Bhaisipati stations showing the largest decrease in median value (26%) compared to mean and Shankapark station showing almost same values of mean and median averages of $PM_{2.5}$. In general, median averages are lower than the corresponding mean averages due to the fact that relatively lower concentration values are higher in frequency than the higher values in all the stations resulting in positively skewed curve.

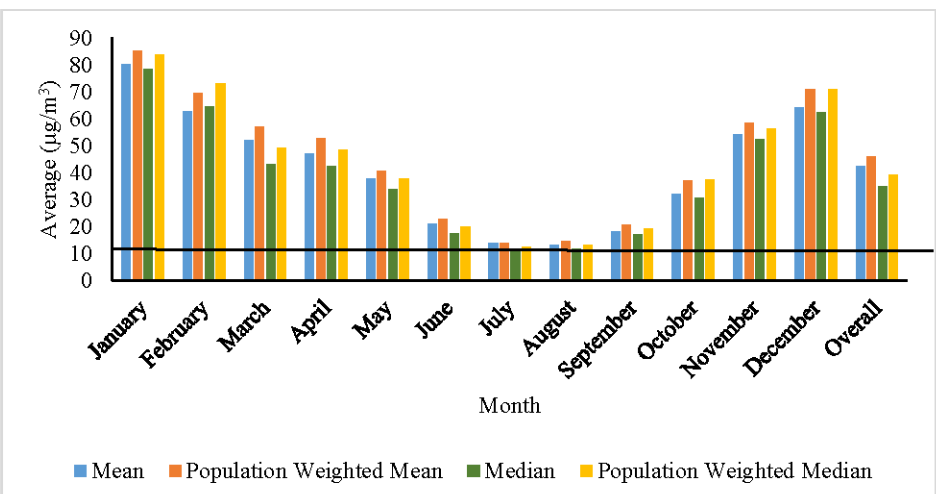
Figure 4 Station-wise variation of $PM_{2.5}$ during 2017–2020 in Kathmandu valley (see online version for colours)



3.4 Monthly variation

The monthly variation of particulate air pollution ($PM_{2.5}$ and PM_{10}) from all measurements in Kathmandu valley showed high seasonal effects with the highest average levels observed during winter months (December, January and February) and lowest average values during the summer rainy season (July, August and September) (Figures 5 and S2). PM_{10} monthly average values measured during 2003–2007 for the winter months were high: January levels averaged 200.4 μg/m^3, February 175.1 μg/m^3, and December 168.9 μg/m^3. Summer months were lowest with 67.2 μg/m^3 in July, 61.4 μg/m^3 August, and 66.8 μg/m^3 in September. The monthly variation in PM_{10} during 2017–2020 showed a similar trend with highest concentrations in winter and lowest in summer. However, overall average concentrations were reduced for these years. Seasonal and monthly variation in $PM_{2.5}$ level is assessed for 2014/15 and 2017–2020. Similar to PM_{10} variation, the seasonal variation of $PM_{2.5}$ showed highest average in winter (82 μg/m^3), then in spring (70 μg/m^3) and autumn and summer (23.7–23.8 μg/m^3) averaged the least in 2014/15. Following the decrease in annual average for the 2017–2020 period, seasonal averages are also significantly decreased during 2017–2020 considering unweighted mean and median averages. As observed, the winter average of $PM_{2.5}$ is found to be 3.5 times higher than in summer (or autumn) season in 2014/15 and 4.1 times higher than summer season in 2017–2020 period. Similarly, the winter population weighted mean is found 4.3 times higher than summer season in 2017–2020 period (Figure 5).

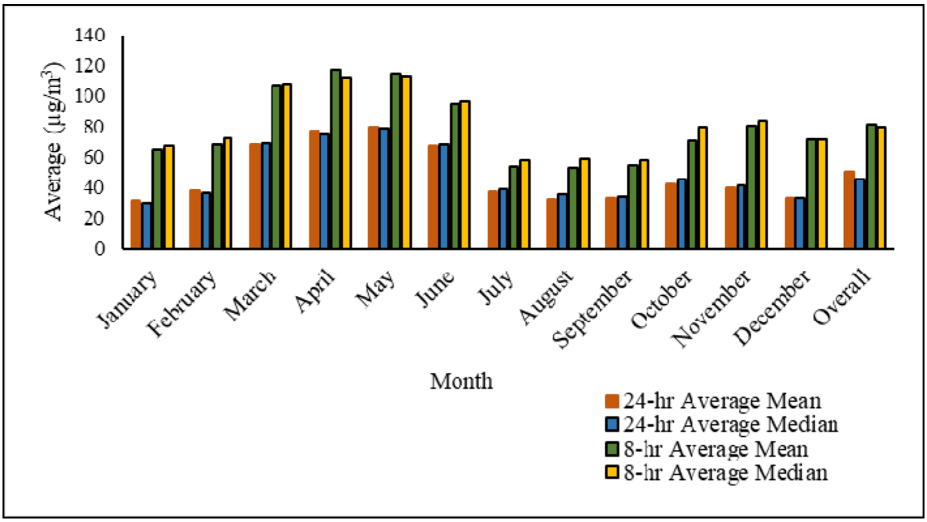
Figure 5 Monthly $PM_{2.5}$ concentration in Kathmandu valley during 2017–2020 (see online version for colours)



Examination of seasonal averages of ozone level in Kathmandu shows highest average in spring considering both 24-hr average mean (74.9 μg/m^3) and 8-hr average mean (113.4 μg/m^3) and least in winter with 33.8 μg/m^3 for 24-hr mean and 68.1 μg/m^3 for 8-hr mean. The overall averages are found to be 50.38 μg/m^3 and 81.78 μg/m^3 regarding 24-hr and 8-hr means, respectively. Similar but slightly lower averages are detected in median values also. Overall, the 8-hr average of O_3 is found to be 1.6 times and 1.7 times higher than 24-hr for mean and median, respectively. The monthly averages show that the maximum monthly average is observed during April – May (77–80 μg/m^3, 24-hr;

115–117 μg/m^3, 8-hr) whereas minimum monthly averages are observed during January (31 μg/m^3, 24-hr; 64.7 μg/m^3, 8-hr). The pattern of monthly variation is found different than observed in case of particulate air pollution and also the pattern of sinusoidal like changes in monthly averages, even though present, is different as it peaks during the drier and warmer pre-monsoon period (April-May) and not during winter months as seen in Ozone monthly variation (Figure 6). It is also notable that monthly averages are low during rainy season (July, August and September) which is likely due to cloudy or rainy days without sunlight and photochemical generation of O_3 in the presence of precursor air pollutants such as NO_X and volatile organic compounds (VOCs).

Figure 6 Monthly ozone level in Kathmandu, 2017–2020 (see online version for colours)



3.5 Daily variation assessed by exceedance outside WHO 2005 guideline

Daily variations of PM_{10}, $PM_{2.5}$ and ozone are assessed by percent above WHO 2005 guidelines based upon data by stations. The annual percent of daily PM_{10} average above WHO guideline of 50 μg/m^3 was very high during 2003–2007 period of monitoring with 72–79% of the averages above the WHO guideline. The NHRC study in 2014/15 showed around 58% of $PM_{2.5}$ averages above WHO guideline of 25 μg/m^3. In 2017, the percent above the guideline was again very high with 84% and 76% of the averages above considering PM_{10} and $PM_{2.5}$, respectively. Thereafter, the percentage has gone down to 51% and 54% for PM_{10} and $PM_{2.5}$, respectively in 2020 (till August). The overall decrease in the percent of PM_{10} in 2017–2020 period compared to 2003–2007 period is 32.6% which is indeed a significant decrease. However, still majority of the daily averages are above the WHO guideline and therefore a major concern in Kathmandu valley. Similarly, the percent observations above WHO guidelines of $PM_{2.5}$ have also gone down from 76% in 2017 to 54% in 2020 (till August). There has been some up and down fluctuation in annual ozone level with an overall 27% above WHO guideline for 2017–2020 period with a substantial decrease in 2020 (till August) compared to 2017 (Table 1). The percentage distribution above WHO guidelines is based upon station-wise data.

Table 1 Percent of observations above WHO 2005 guidelines

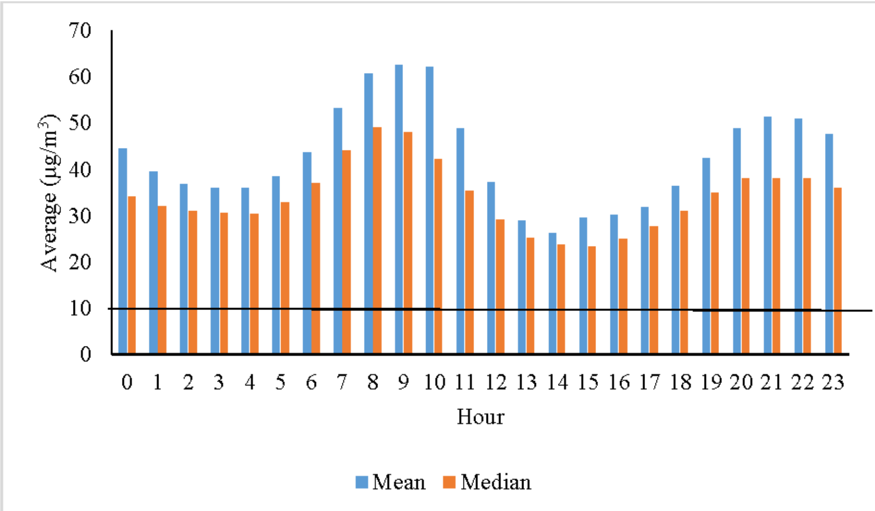
Year	PM_{10}	$PM_{2.5}$	*Ozone*
2003	78.7	NA	NA
2004	79.7	NA	NA
2005	75.2	NA	NA
2006	72.6	NA	NA
2007	73.1	NA	NA
2014/15	NA	57.6	NA
2017	84.4	75.5	39.6
2018	32.8	61.8	22.5
2019	55.6	59.7	25.0
2020 (till August)	50.9	54.4	18.3
2003–2007	76.0	NA	NA
2017–2020	51.2	61.6	27.0

NA: Not available

3.6 Diurnal variation

Within 24-hr variation of air pollution is important for air pollution assessment since it gives us information on how air pollution changes in day time and night time and during what time levels peak and minimise. It can be dependent upon various factors primarily upon emissions and also local atmospheric parameters like temperature, humidity, rainfall or wind and situations like sunshine, cloudy, rainy or windy conditions. The bowl shaped topographic condition within Kathmandu valley also plays an influencing factor in changes of levels in the ambient air. Examination of the variation (2016–2020) reveals that PM_{10} and $PM_{2.5}$ levels are found to be at lowest levels after midnight at around 3 AM early morning (36 $\mu g/m^3$) and starts to increase throughout morning time and peaks around 9 AM ($PM_{2.5}$: 62 $\mu g/m^3$; PM_{10}: 80 $\mu g/m^3$) and then slowly decreases till afternoon around 2 PM ($PM_{2.5}$: 26 $\mu g/m^3$; PM_{10}: 55 $\mu g/m^3$), then gradually increase till 8–9 PM evening ($PM_{2.5}$: 52 $\mu g/m^3$; PM_{10}: 68 $\mu g/m^3$) and decrease thereafter till 3 AM after midnight (Figure 7 and Supplementary Figure S3). The variation is like a sine curve with gradual ups and downs throughout 24-hr duration. The diurnal variation in PM concentrations have also been studied earlier in Kathmandu valley which showed low values in afternoon and at night, peaks in morning and evening time (Panday and Prinn, 2009; Panday et al., 2009). It is also interesting to note that the proportion of hourly $PM_{2.5}$ concentration compared to PM_{10} changes smoothly within 24-hr with maximum (0.86) after midnight (1–4 AM) and then decreases gradually throughout morning and reaches minimum (0.55) during afternoon (2 PM) and again increases throughout evening and night and attains maximum after midnight (Supplementary Figure S4). This diurnal change in the proportion of $PM_{2.5}$ could be due to changes in $PM_{2.5}$ emission at different times within 24-hr and also due to fine particles settling down at surface level relatively more during night due to cold temperature and absence of wind, and wind-blown dust particles would be higher in daytime with more vehicles on the road and winds. The hourly PM_{10} averages in Kathmandu valley are provided in the Supplementary material (Supplementary Figure S3).

Figure 7 Hourly average $PM_{2.5}$ in Kathmandu valley (2016–2020) (see online version for colours)



3.7 *Air pollution and 2020 spring lockdown due to COVID-19*

The lockdown situation in Kathmandu valley due to COVID-19 pandemic effect has affected air pollution condition in Kathmandu valley mainly due to substantial reduction in vehicular movements, though other activities like construction works were also halted during lockdown. Brick production is seasonal in Nepal and operates mostly during winter from November to April/May. The lockdown period was imposed mostly in summer time and therefore could have minimum effect on air pollution due to absence of brick kiln production during lockdown. To examine the extent of effect due to lockdown in Kathmandu valley, air pollution levels are examined during the lockdown period compared to the same time period one year before in 2019 in order to nullify the seasonal and meteorological effects as far as possible though annual trend cannot be ruled out. Lockdown was imposed in Nepal including Kathmandu valley from 24 March, 2020 till 21 July, 2020 in the first phase. In the second phase another lockdown was imposed in the valley from 17 August, 2020 till 9 September, 2020. The air pollution averages in the lockdown period in 2020 and same time period prior one year (2019) showed that indeed there has been a substantial decrease in air pollution levels regarding $PM_{2.5}$ air pollution with 34.6% decrease from 31.2 $\mu g/m^3$ to 20.4 $\mu g/m^3$ in the lockdown period. A recent study of ambient air quality using air quality index (AQI) for PM_{10} and $PM_{2.5}$ in 2020 compared air quality of Kathmandu before and during the lockdown period. The study found that the ambient air pollution decreased to a moderate zone during the lockdown period. Specifically, the study found AQI for $PM_{2.5}$ decreased from the unhealthy zone to moderate zone at different stations of Kathmandu. AQI for PM_{10} was found to lie inside moderate and good zone (Gautam et al., 2020). Similarly, Baral and Thapa (2021) found that in six cities of Nepal (Damak, Simara, Kathmandu, Pokhara, Nepagunj and Surkhet), AQI for $PM_{2.5}$ and PM_{10} were in moderate zone for the maximum number of days during the lockdown period with statistically significant drop in mean concentrations during the period compared to the corresponding period in 2019.

3.8 Health burden from ambient air pollution

Ambient air pollution has been associated to different major health conditions, diseases and deaths in the world. Studies conducted in Nepal particularly in Kathmandu valley have demonstrated links through analysis and modelling based upon local data generated from air pollution monitoring, meteorological and health data. Daily air pollution data on PM_{10} were obtained through fixed monitoring stations within the valley, corresponding meteorological and hospital data have been used by NHRC study (Khanal and Shrestha, 2006) funded by WHO in 2005 and short term health effect coefficients related to mortality and respiratory ailments like chronic obstructive pulmonary disease (COPD), pneumonia, bronchitis and asthma were quantified using generalised linear model based upon ecological time series design. Later on, the data was reanalysed to obtain distributed lag effects of PM_{10} (Shrestha, 2007; Shrestha, 2012). Before the NHRC study, health effect assessments were based upon health effect coefficients obtained from studies conducted at other parts of the world mainly in US and European countries and results were extrapolated. In 2014/15, a study again conducted by NHRC (also funded by WHO) installed three fixed stations in the valley and air pollutants namely $PM_{2.5}$, CO and NO_2 were continuously measured for a whole one year. Effects of the pollutants on various health conditions were studied namely respiratory problems like COPD, acute respiratory infection (ARI), pneumonia and health effects were quantified using statistical models accounting distributed lag effects which were used for determination of attributable factors and corresponding attributable burdens in Kathmandu valley. In 2017, Gurung et al. (2017) quantified health effects related to cardiovascular problems based upon earlier air pollution monitoring data of PM_{10} during 2003–2007 phase of monitoring by MOPE in which case-crossover design based analysis was performed (Gurung and Bell, 2017). Different health effect coefficients estimates are summarised in Table 2. The health burden data obtained from DoHS for the year 2016/17 is given in Table 3. Burdens include mortality and morbidities for different respiratory diseases usually accounted in burden of disease assessment related to air pollution exposure. Since these estimates are based upon local estimates, they offer an important input to produce estimates that can be compared to estimates based upon meta-analysis of studies conducted using various studies from all over the world. Consequently, estimates based upon meta-analysis are considered and attributable burdens are also calculated using AirQ + software developed by WHO for estimating attributable and avoidable burden of diseases (WHO, 2019; Sacks et al., 2020). Different statistical methods have been applied to obtain local estimates such as generalised linear model (GLM), generalised additive model (GAM), semiparametric GAM and conditional logistic regression for case-crossover design.

Table 2 Health effect estimates of air pollution obtained from studies in Kathmandu valley

Health effect	*Estimate*	*95% CI*	*Lag effect*	*Model*	*Year*	*References*
Effect from PM_{10}						
All cause mortality	0.7%	–	Short term	GLM	2005	Khanal and Shrestha (2006)

Table 2 Health effect estimates of air pollution obtained from studies in Kathmandu valley (continued)

Health effect	*Estimate*	*95% CI*	*Lag effect*	*Model*	*Year*	*References*
Respiratory admission (COPD, Asthma, Pneumonia, Bronchitis)	1.9%	–	Short term	GLM	2005	Khanal and Shrestha (2006)
COPD admission	3.2%		Short term	GLM	2005	Khanal and Shrestha (2006)
Respiratory admission	1.7%	0.18–3.25%	Short term	Case–crossover, Conditional logistic	2004–2007	Gurung et al. (2017)
Cardio-vascular admission	2.29%	0.18–4.43%	Short term	Case-crossover Conditional logistic	2004–2007	Gurung et al. (2017)
All cause mortality	2.6%	0.7–4.6%	DL, 3 weeks	Autoregressive semi-parametric GAM	2005	Shrestha (2012)
Respiratory admission (COPD, Asthma, Pneumonia, Bronchitis)	3.5%	2.11–5.04%	DL, 6 weeks	GLM	2005	Shrestha (2007)
Respiratory admission (COPD, Asthma, Pneumonia, Bronchitis)	3.5%	2.05–4.99%	DL, 6 weeks	GAM	2005	Shrestha (2007)
COPD admission	4.9%	3.10–6.64%	DL, 4 weeks	GLM	2005	Shrestha (2007)
COPD admission	4.8%	2.84–6.65%	DL, 4 weeks	GAM	2005	Shrestha (2007)
Effect from $PM_{2.5}$						
COPD	1.61%	0.22–3.02%	Short term	GLM	2014/15	NHRC (2016)
ARI admission	2.02%	0.43–3.64%	DL, 7 day	GLM	2014/15	NHRC (2016)
Pneumonia admission	3.36%	1.14–5.61%	DL, 7 day	GLM	2014/15	NHRC (2016)
Respiratory admission	1.00%	0.02–2.00%	Short-term	Autoregressive GLM	2014/15	NHRC (2016)
All cause mortality	3.7%	–	DL, 7 day	GLM	2014/15	NHRC (2016)

In the following assessment, health burden that can be attributable to ambient $PM_{2.5}$ in Kathmandu valley is estimated based upon health effect coefficients obtained from earlier 2014/15 NHRC study. The current air pollution monitoring observations and the total health burden of some specific diseases related to air pollution exposure are used. Environmental burden of disease (EBD) assessment is performed in the following steps:

- use of exposure-response coefficients considering different health effects namely all cause mortality, respiratory, COPD, ARI and pneumonia
- construction of frequency table of $PM_{2.5}$ exposures and relative risks at different level of exposures
- taking account of total burden for baseline period and estimated burden for future period (2030) considering population growth
- computation of attributable fractions and attributable burdens
- computation of avoidable burdens for assumed improved scenarios
- air pollution risk factors are considered separately for ambient air pollution and brick kiln air pollution.

Attributable burden related to mortality is also computed and assessed since a couple of Sustainable Development Goals (SDG) indicators is related to this measure (SDG Indicator 3.9.1: Mortality rate attributed to household and ambient air pollution).

3.9 Attributable burden due to $PM_{2.5}$

The estimated attributable fractions (AFs) due to $PM_{2.5}$ show highest AF estimated for pneumonia morbidity with around 12.8% attributed to $PM_{2.5}$ ambient air pollution, followed by ARI (7.9%), COPD (6.3%) and respiratory (4%). The corresponding attributable burden is highest for ARI and respiratory morbidity (11 thousand each or 445 per 100 thousand) followed by pneumonia morbidity (5.5 thousand or 223 per 100 thousand) and COPD (3.3 thousand or 134 per 100 thousand) (Table 3). The avoidable burden is estimated for alternate improved scenarios for the year 2030 with hypothesised reduction of 35% termed as business as usual (BAU) scenario and 60% termed as progressive scenario. The percentage reduction in BAU scenario is hypothesised based upon reduction in $PM_{2.5}$ air pollution over the recent past years of available monitoring averages in Kathmandu valley with around 4–5% reduction each year. Similarly, the progressive scenario is hypothesised under very optimistic implementations of major steps required for such a reduction with an average of around 8% reduction in average each year. Examination of avoidable burdens depict that highest reduction is expected for respiratory and ARI morbidity with reduction of around 6.3 thousand cases each (174 per 100 thousand) followed by 3.1 thousand pneumonia cases (86 per100 thousand) and around 1.9 thousand avoidable COPD cases (52 per 100 thousand) for BAU scenario. For around double percentage reduction (60%) in $PM_{2.5}$ average in progressive scenario, the avoidable burdens are also around double compared to BAU scenario (Table 4).

For computation, population of Kathmandu valley is taken as 2.47 Million (United Nations, 2017), Crude Death Rate of Nepal taken as 6.4 per thousand (World Bank, 2020), urban population growth rate taken as 3.9% as per World Bank, 2019 which is equivalent to 3.62 million in 2030.

Table 3 Attributable fraction and attributable burden from $PM_{2.5}$ ambient air pollution in Kathmandu valley

Health effect	*Coefficient*			*Attributable fraction*			*Total Burden**	*Attributable burden*		
	Central	*Lower*	*Upper*	*Central*	*Lower*	*Upper*		*Central*	*Lower*	*Upper*
COPD	0.0016	0.0002	0.0030	0.0630	0.008	0.1167	51951	3273	416	6063
ARI	0.0020	0.0004	0.0036	0.0785	0.0159	0.1393	140841	11056	2239	19619
Pneumonia	0.0033	0.0011	0.0055	0.1281	0.0435	0.2092	42929	5499	1867	8981
Respiratory	0.0010	0.00002	0.00198	0.0396	0.0008	0.0777	281556	11150	225	21877

Threshold value for $PM_{2.5}$ = 5 µg/m^3 (Ostro, 2004); * Total number of individuals affected.

Table 4 Avoidable fraction and avoidable burden from $PM_{2.5}$ ambient air pollution in Kathmandu valley

Health effect	*Alternate Scenario*	*Avoidable AF*			*Total Burden (in 1000)*	*Avoidable burden*		
		Central	*Lower*	*Upper*		*Central*	*Lower*	*Upper*
COPD	BAU (35% Reduction)	0.0246	0.0032	0.045	76	1870	243	3420
ARI		0.0306	0.0063	0.0535	206	6304	1298	11021
Pneumonia		0.0493	0.017	0.0791	63	3106	1071	4983
Respiratory		0.0155	0.0003	0.0302	412	6386	124	12442
COPD	Progressive (60%) Reduction	0.0419	0.0054	0.0772	76	3184	410	5867
ARI		0.0512	0.0106	0.0885	206	10547	2184	18231
Pneumonia		0.0846	0.029	0.137	63	5330	1827	8631
Respiratory		0.0264	0.0005	0.0516	412	10877	206	21259

3.10 Attributable burden using AirQ + software developed by WHO

Attributable and avoidable burdens are also computed and assessed using WHO AirQ + software for which local data based health effect estimates are unavailable as of now. For the purpose, different input values are obtained and used as follows for 2017–2020 baseline period. Additionally, the relative risk estimate of mortality equivalent to 1.062 (1.040–1.083) obtained from WHO study, "Health risks of air pollution Europe-HRAPIE project" is also used for burden of disease calculation (Chan and Henschel, 2013).

Population of Kathmandu valley: 2.47 Million; percent of population aged 30 or above = 62.34% is equivalent to 1.54 Million; $PM_{2.5}$ = overall mean = 42.4; CDR = 6.38 per 1000 (2017–2018); RR (mortality) = 1.0123 (1.0045–1.0201); Threshold value for $PM_{2.5}$ = 5 μg/m^3 (Ostro, 2004); Urban population growth rate: 3.9% as per World Bank, 2019 equivalent to 2.27 million in 2030 for aged 30 and above (or 3.62 million total population); CDR decreasing at 0.9% annually from last 10 years data is equivalent to 5.83 per 1000 in 2030.

Using the above input values for the baseline period, avoidable mortality is computed for 35% reduction in $PM_{2.5}$ level taken as BAU scenario and 60% reduction in $PM_{2.5}$ concentration taken as progressive scenario in the year 2030. Results show that around 80 and 245 deaths can be avoided per year in Kathmandu valley assuming BAU and progressive scenario, respectively (Table 5A) using AirQ + software and 300 and 1060 assuming BAU and progressive scenario, respectively using WHO HRAPIE estimate (Table 5B). Evidently, avoidable cases using WHO HRAPIE estimate is much higher compared to WHO AirQ + software due to higher estimate of relative risk using WHO HRAPIE study.

Table 5A Mortality (Aged 30 and above) attributable and avoidable fractions and burdens from $PM_{2.5}$ ambient air pollution in Kathmandu valley using WHO AirQ + software

Period	*Measure*	*Attributable*			*Avoidable*		
		Central	*Lower*	*Upper*	*Central*	*Lower*	*Upper*
Baseline (2017–2020)	Attributable fraction	0.0447	0.0166	0.0717	–	–	–
	Attributable cases	439	164	705	–	–	–
	Attributable cases per 100, 000 population at risk	28.51	10.62	45.76	–	–	–
BAU (35% Reduction) 2030	Attributable/Avoidable fraction	0.0272	0.0101	0.0439	0.0175	0.0065	0.0278
	Attributable/Avoidable cases	360	133	581	79	31	124
	Attributable/Avoidable cases per 100, 000 population at risk	15.86	5.87	25.59	12.65	4.75	20.17
Progressive (60% Reduction) 2030	Attributable/Avoidable fraction	0.0146	0.0054	0.0236	0.0301	0.0112	0.0481
	Attributable/Avoidable cases	193	71	312	246	93	393
	Attributable/Avoidable cases per 100, 000 population at risk	8.49	3.13	13.76	20.02	7.49	32

Table 5B Mortality (Aged 30 and above) attributable and avoidable fractions and burdens from $PM_{2.5}$ ambient air pollution in Kathmandu valley using WHO HRAPIE estimate

Period	Measure	Attributable			Avoidable		
		Central	Lower	Upper	Central	Lower	Upper
Baseline (2017–2020)	Attributable fraction	0.2015	0.1364	0.2579	–	–	–
	Attributable cases	1979	1340	2533	–	–	–
	Attributable cases per 100, 000 population at risk	128.53	87.05	164.51	–	–	–
BAU (35% Reduction)	Attributable/Avoidable fraction	0.1269	0.0847	0.1646	0.0746	0.05175	0.09322
	Attributable/Avoidable cases	1679	1121	2179	300	220	355
	Attributable/Avoidable cases per 100, 000 population at risk	73.98	49.37	95.98	54.55	37.68	68.53
Progressive (60% Reduction)	Attributable/Avoidable fraction	0.0694	0.0458	0.0910	0.1320	0.0906	0.1669
	Attributable/Avoidable cases	919	606	1204	1061	734	1330
	Attributable/Avoidable cases per 100, 000 population at risk	40.47	26.72	53.03	88.06	60.33	111.48

3.11 Health burden from brick kilns

An interesting analysis has been carried-out with specific focus on air pollution due to brick kilns activities. This analysis addresses the potential effects, in particular on respiratory diseases, of one of the sector responsible for significant emissions. Air pollution from brick kilns is a major source of air pollution in Kathmandu valley as from vehicular emission. Studies have associated mainly respiratory problems with brick kiln workers and population exposed to brick kilns residing near to these areas in Kathmandu valley and compared health effects to those exposed and unexposed to brick kiln emissions such as respiratory diseases like chronic bronchitis and asthma and respiratory symptoms like cough, phlegm and wheezing. Findings of two such studies based upon local data and clinical examinations of exposed and unexposed populations are assessed for computation of attributable fractions. Findings of the studies are given in Table 6.

Data of population exposure to brick kiln emission is available only for the professional workers in Kathmandu valley and not for local inhabitants. Attributable fractions are therefore estimated only for brick kiln workers with estimated 25000 brick kiln workers in Kathmandu valley during 2016/17. For the period 2017–2019, the attributable burdens per year are estimated in the following Table 7 for different health effects. Total health burden data is obtained from DoHS annual health burden including inpatients and outpatients. Attributable health burden among brick kiln workers in Kathmandu valley assessed for the period 2017–19 shows around 0.9% and 2%

attributable to brick production emission with corresponding attributable burdens 200 and 500 for chronic bronchitis and asthma morbidity, respectively (Table 7).

Table 6 Health effect estimates from brick kiln air pollution obtained from studies in Kathmandu valley, Nepal

Health effect	*OR**	*95% CI*	*Analysis/model*	*Year*	*References*
Tonsillitis	4.17	2.05–8.45	Cross-tab frequency Children, controlling smoking and age	2004/05	Joshi and Dudani (2008)
Acute pharyngitis	4.08	2.01–8.33	Cross-tab frequency Children, controlling smoking and age	2004/05	Joshi and Dudani (2008)
Cough	2.35	1.14–7.85	Logistic regression, adjusted for age, duration of work and smoking	2015/16	Sanjel et al. (2017)
Phlegm	2.98	1.07–8.24	Logistic regression, adjusted for age, duration of work and smoking	2015/16	Sanjel et al. (2017)
Wheezing	6.00	2.78–12.94	Logistic regression, adjusted for age, duration of work and smoking	2015/16	Sanjel et al. (2017)
Bronchitis	1.91	1.26–2.9	Logistic regression, adjusted for age, duration of work and smoking	2015/16	Sanjel et al. (2017)
Asthma	3.18	1.31–7.58	Logistic regression, adjusted for age, duration of work and smoking	2015/16	Sanjel et al. (2017)

*OR = Odds ratio.

Table 7 Attributable fraction and attributable burden from brick kiln air pollution in Kathmandu valley

			*PAF**				*Attributable Burden*		
Outcome	*RR**	*95% CI**	*Central*	*Lower*	*Upper*	*Total Burden*	*Central*	*Lower*	*Upper*
Chronic Bronchitis	1.91	1.26–2.90	0.0090	0.0026	0.0186	22270	200	58	414
Asthma	3.18	1.31–7.58	0.0213	0.0031	0.0617	23565	495	73	1454

*RR = Relative risk; CI = Confidence interval; PAF = Population attributable fraction.

3.12 Avoidable burdens from brick kiln

Avoidable burden is calculated taking account of existing emission standards and proposed emission standards for different types of brick kilns as shown in Table 9. Table 8 shows annual brick production in Kathmandu valley with suspended particulate matter (SPM) emission. Around 42% reduction in emission standard as regards to particulate matter is proposed. Alternate emission reduction scenarios are therefore, taken as 30% to 50% within 10 years (2030).

Table 8 Emission from brick kiln by their type

Kiln Type	*Kilns*	*Annual brick production* (million)	*Annual brick production* (1000 tons)	*SPM emission* (mg/Nm^3)
Fixed Chimney Bull's Trench Kiln (FBTK)	107	612	1242.36	326
Hoffman	2	8	16.24	374
Vertical Shaft Brick Kiln (VSBK)	1	40	81.2	144
Total/Average	110	660	1339.8	281.33

Source: MOPE, 2017; Weight per brick = 2.03 kg

Table 9 Existing and proposed emission standards of brick kilns

Kiln type	*Existing standard* (mg/Nm^3)	*Proposed standard* (mg/Nm^3)	*Percent reduction*
Bull's Trench Kiln (BTK), induced draft	600	250	58
BTK, natural draft	700	500	29
VSBK	400	250	38

Source: MOPE (2017)

Around 80 and 210 cases are estimated to be avoidable among brick kiln workers regarding chronic bronchitis and asthma cases in Kathmandu valley for 30% reduction of emission scenario, respectively. Similarly, around 145 and 360 cases are estimated to be avoidable among brick kiln workers regarding chronic bronchitis and asthma cases in Kathmandu valley for 50% reduction of emission scenario, respectively (Table 10).

Table 10 Avoidable fraction and burden attributable to brick kiln air pollution

	30% Reduction in emission			*50% Reduction in emission*		
Outcome	*Avoidable PAF*	*Total Burden (in 1000)*	*Avoidable Burden*	*Avoidable PAF*	*Total Burden (in 1000)*	*Avoidable Burden*
Chronic Bronchitis	0.0025	32.5	81	0.0044	32.5	143
Asthma	0.0061	34.4	210	0.0104	34.4	358

4 Discussion

4.1 Air pollution status

Air pollution in Kathmandu valley has decreased steadily and significantly in the recent years compared to around fifteen years back during when 24-hr continuous monitoring throughout the year started with installation of fixed stations at different places in Kathmandu valley. Annual averages of monitored levels show that the concentration levels of PM_{10} have gone down by around half of its value observed in 2018–2020 compared to 2003–2007. Compared to 2014/15 annual average of $PM_{2.5}$ (49.1 μg/m^3), the average has reduced significantly by 13.6% in around 4 years. Similarly, the median averages of particulate air pollution which are slightly lower than the mean values have also decreased substantially from 2003–2007 to 2018–2020 by around 55.6% for PM_{10} and population weighted mean values also decreased significantly by 37.8% during the recent years (2018–2020). Even though the decrease in particulate air pollution in Kathmandu valley has been substantial over the past years the annual averages are still very high compared to the WHO 2005 guidelines for PM_{10} (3 times higher) as well as for $PM_{2.5}$ (4 times higher). Regarding annual variation of ozone level, monitoring data is available only from 2017 onwards and shows that annual round the clock monitoring has remained more or less same to around 50 μg/m^3 whereas the annual averages computed from daily 8-hr measurements during day time has decreased marginally with the overall average of 82 μg/m^3. It is to be noted that though the stations covered during 2003–2007, 2014/15 and the current ongoing monitoring since 2016 are not exactly at the same locations but the types of areas covered are more or less similar in every phase of monitoring. For instance, during 2003–2007 period, monitoring stations covered high traffic areas, medium traffic areas and residential areas, low traffic and background areas and stations were installed in all the three districts of Kathmandu valley. Similarly, 2014/15 monitoring stations and the currently installed stations also covered all the three types of areas and districts of Kathmandu valley so that the averages obtained from different phases of monitoring are logically comparable.

Even though population of Kathmandu valley has increased substantially during the last one and half decades and so have vehicular movements, still PM_{10} and $PM_{2.5}$ levels have gone down significantly in Kathmandu. This can be attributed to various factors such as implementation of government plans and policies and rules and regulations regarding urban air quality management measures with ban of old vehicles 20 or more years old and two-stroke engine operated motorbikes, relatively more concrete, paved and cleaner roads with less amount of resuspension of dust particles than years before and use of modern technologies including vehicles run from batteries. The population weighted measures are found slightly lower than the unweighted averages regarding mean and median values in the valley in earlier 2003–2007 phase of monitoring. However, in the recent years, the population weighted PM_{10} levels are found higher compared to unweighted levels. This could be due to rapid growth of population in core areas compared to peripheral areas within the valley and also could be due to accounting of relatively more core areas in recent monitoring compared to earlier monitoring. It is also evident that median values are lower than corresponding mean values since 2003 onwards repeatedly even during the recent years which indicates positively skewed frequency distribution of concentration with higher occurrence of lower levels than the higher values. Station-wise levels also show relatively higher $PM_{2.5}$ levels in Kathmandu stations like Ratnapark, US embassy station and Phora Darbar stations (47–55 μg/m^3) which are relatively much higher traffic areas and core areas of Kathmandu. Stations like Bhaktapur, Bhaisipati, Pulchowk and Shankapark stations which are relatively less traffic density areas showed much lower $PM_{2.5}$ averages (20–35 μg/m^3). This again demonstrates that vehicular emission and dust resuspension from vehicular traffic as large sources of air pollution in Kathmandu valley.

Dry and cold seasons like winter and spring with low temperatures and rainfall showed relatively much higher $PM_{2.5}$ concentrations (46–69 μg/m^3) compared to summer and monsoon season (17–36 μg/m^3) with averages about 2 times higher in dry and winter months. Similar results are obtained for PM_{10} also but a marked difference in seasonal averages has been detected in case of ozone level. Results show that the average is highest in spring months (75 μg/m^3) and summer (47 μg/m^3) compared to winter (34 μg/m^3) and autumn (39 μg/m^3). Higher surface ozone concentrations observed during the warmer months can be attributed to the high intensity of solar radiation and high temperature levels which promote the photochemical generation of O_3 (Selvaraj et al., 2013). The percent observations above WHO 2005 guideline is one of the major indicators of the extent of air pollution in the ambient air. During 2003–2007 phase of monitoring this percentage of PM_{10} was around 76% which is about 1.5 times higher than observed during 2017–2020 monitoring (51.2%). Also, about 60% of observations in 2014/15 monitoring as well as during 2017–2020 was found above the WHO 2005 guideline of 24-hr average $PM_{2.5}$ in Kathmandu valley.

Diurnal variation of air pollution levels can be dependent upon various factors primarily upon emission and local atmospheric parameters like temperature, humidity, rainfall or wind and situations like sunshine, cloudy, rainy or windy conditions. The bowl shaped topographic condition within Kathmandu valley also plays influencing factor in levels of air pollutants in the ambient air. Examination of the variation reveals that PM_{10} and $PM_{2.5}$ levels are found to be at lowest levels after midnight at around 3 AM early morning and starts to increase throughout morning time and peaks around 9 AM and then slowly decreases till afternoon around 2 PM, then gradually increase till 8–9 PM evening and decrease thereafter till 3 AM after midnight. The variation is like a sine curve with gradual ups and downs throughout 24-hr duration. Similar sine curve like variation during morning, afternoon, evening and night time variation have been observed in NHRC study in 2014/15 though morning time peak was slightly early during 8–9 AM and very interesting to note that concentration levels minimise during day time most probably due to heating effect on the surface and more winds during day time compared to morning time.

4.2 Health burden from air pollution

Health burden from air pollution in Kathmandu valley assessed through attributable and avoidable fractions and burdens show highest attributable fraction for pneumonia morbidity with around 12.8% attributed to $PM_{2.5}$, followed by ARI (7.9%), COPD (6.3%) and respiratory (4%). The corresponding attributable burden is highest for ARI and respiratory morbidity (11000 each) followed by pneumonia morbidity (5500) and COPD (3300). Examination of avoidable burdens depict highest reduction for respiratory and ARI morbidity with reduction of around 6.3 thousand cases each followed by 3.1 thousand pneumonia cases and around 1.9 avoidable COPD cases for BAU (35% reduction) scenario. For around double percentage reduction (60%) in $PM_{2.5}$ average in progressive scenario, the avoidable burdens are also around double compared to BAU scenario. Avoidable burdens are also computed and assessed using WHO AirQ + software for which local data based health effect estimates are currently unavailable. Compared to the baseline period (2017–2020), avoidable mortality is computed for BAU scenario and progressive scenario for the year 2030. Results show that around 80 to 245 deaths can be avoided per year in Kathmandu valley assuming BAU and progressive scenarios, respectively regarding $PM_{2.5}$.

Considering health effects from brick kiln exposure, attributable health burden among brick kiln workers in Kathmandu valley assessed for the period 2016–2017 shows around 0.9% and 2% attributable to brick production emission with corresponding attributable burdens 200 and 500 for chronic bronchitis and asthma morbidity, respectively. Regarding avoidable burdens calculated for 30–50% reduction in brick kiln emission, around 80 and 210 cases are estimated to be avoidable among brick kiln workers regarding chronic bronchitis and asthma cases in Kathmandu valley in 30% reduction of emission scenario and around 145 and 360 cases are estimated to be avoidable among brick kiln workers regarding chronic bronchitis and asthma cases in Kathmandu valley in 50% reduction of emission scenario.

The findings of the study are confined to Kathmandu valley. However, since ambient air quality of many urban areas outside the valley is also found to be poor in Nepal (Baral and Thapa, 2021), the public health concerns associated to ambient air pollution is undoubtedly a critical issue to the exposed inhabitants of urban areas outside the valley. Moreover, further researches related to air pollution and health are necessary in urban areas outside the valley as studies are very much limited so far.

4.3 Limitations

Our study has a number of limitations. The data availability was not optimal, with issues of coverage of measurements for some stations such as O_3 was available only for two stations and there are some missing observations for both $PM_{2.5}$ and PM_{10} though their overall effects on averages are considered to be minimal. We have used risk estimates from both local and meta-analysis studies. In some cases, we can expect an over-estimation of the burden, as well as of the health benefits associated with reduced pollution. But, results should be interpreted as conservative, because some relevant pollutants were excluded from the analysis (e.g., ozone and NO_2), although their relative contribution to health morbidity and mortality is likely to be relatively small compared with PM. Notwithstanding these limitations, both our results and previous ones highlight the urgency of reducing the exposure to particulate matter in Kathmandu.

5 Conclusion

Even though annual air pollution averages of PM_{10} and $PM_{2.5}$ have gone down significantly in the recent years compared to past, the levels are still 3-4 times higher than WHO 2005 guidelines in Kathmandu valley which ascertains that air pollution is still a serious threat to health issues in Kathmandu valley. Findings on attributable burdens also suggest substantial public health burdens regarding mortality and morbidities like respiratory problems including ARI, pneumonia, COPD, bronchitis and asthma. Though health effects are due to multidimensional factors including age, economic condition, nutrition, susceptibility, etc, environmental factors including air pollution is a major risk factor as indicated by studies around the world and so has studies conducted in Nepal and specifically in Kathmandu valley including the present study. In order to reduce public health burdens related to air pollution, reduction in environmental risk factors like air pollution is unavoidable primarily in the context of public health burden concerns for Kathmandu valley inhabitants.

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Supplementary Material of the paper entitled: Air pollution exposure and health impacts in the Kathmandu valley

WHO estimates

Particulate matter (PM), CO and NO_2 pollution in major cities of developing countries including Nepal is considered as major risk factor of environmental burden of disease (EBD). Acute respiratory infection (ARI) has been one of the most important health problems in Nepal. According to WHO estimates, particulate air pollution measured by PM_{10} during the period 2008–2015 in cities of South East Asian countries was above 130 ug/m^3 which is around 6 times higher considering annual average of 20 ug/m^3. The annual median average of $PM_{2.5}$ in Nepal was 64 ug/m^3 in 2012 including urban and rural areas and 74 ug/m^3 in urban areas only. Data shows around 19% of ALRI in children below 5 years of age, 10% of COPD among 25 and above age, 33% of lung cancer among 25 and above age, 19% of IHD among 25 and above age, and 19% of stroke among 25 and above age can be attributed to ambient air pollution considering disability adjusted life years (DALYs) in 2012 (WHO, 2016).

EBD assessment expression

AF for each accounted health effect is calculated by the following expression used by WHO for EBD assessment.

$$AF = \frac{\sum_{i=1}^{k} P_i \left(RR_i - 1 \right)}{1 + \sum_{i=1}^{k} P_i \left(RR_i - 1 \right)}$$

where P_i = Proportion of daily measurements in *i*th category of air pollution exposure; RR_i = Relative risk of the in *i*th category of air pollution exposure obtained from exposure-response modelling. Attributable burden is calculated as: $\text{AF} \times \text{Total burden}$

PM_{10} annual trend

Between 2003 and 2007, annual PM_{10} average (computed from 24-hr daily average and six fixed stations) declined marginally from 134 μg/m^3 to 116 μg/m^3 in the ambient in Kathmandu which amounts to 13.4% decline with average hovering around 123 μg/m^3. The figure is around 6 times higher than the WHO 2005 annual guideline value of 20 μg/m^3. The average PM_{10} in the recent years (2018-August 2020) is found to be around 61 μg/m^3 which is an evidence of substantial decline to half in PM_{10} annual average in the recent years compared to around 15 years earlier. However, the recent average is still 3 times higher than the annual WHO 2005 guideline. Even though population of Kathmandu valley has increased substantially during the last one and half decade and so has vehicular movements, still PM_{10} levels have gone down significantly in Kathmandu. The population weighted measures computed by weighting daily particulate air pollution with district-wise population for the stations are found slightly lower than the unweighted averages regarding mean and median values in the valley in earlier 2003–2007 phase of monitoring. However, in the recent years, the population weighted PM_{10} levels are found higher compared to unweighted levels. This could be due to rapid growth of population in core areas compared to peripheral areas within the valley and also could be due to accounting of relatively more core areas in recent monitoring compared to earlier monitoring. It is also evident that median values are lower than corresponding mean values since 2003 onwards repeatedly even during the recent years which indicates positively skewed frequency distribution of concentration with higher occurrence of lower levels than the higher values.

Figure S1 Annual PM_{10} concentration ($\mu g/m^3$) in Kathmandu valley (see online version for colours)

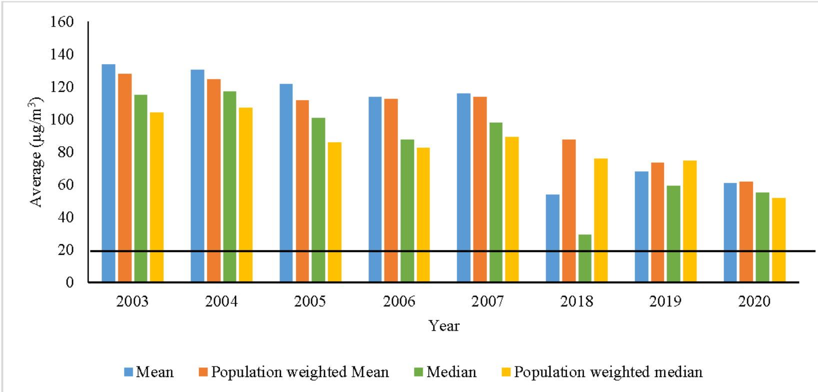


Figure S2 Monthly PM_{10} in Kathmandu valley during 2003–2007 (see online version for colours)

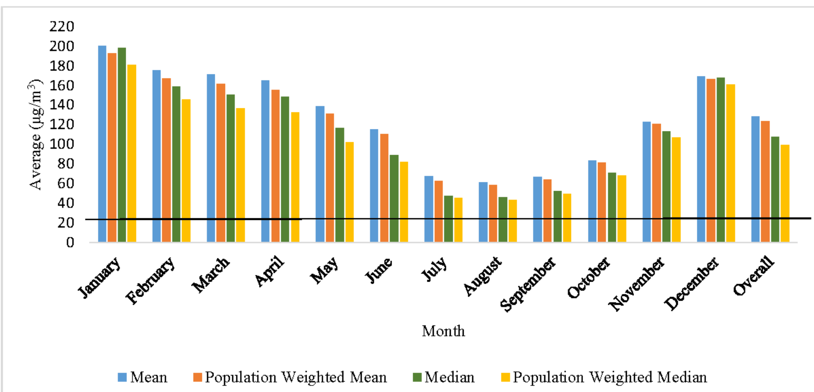
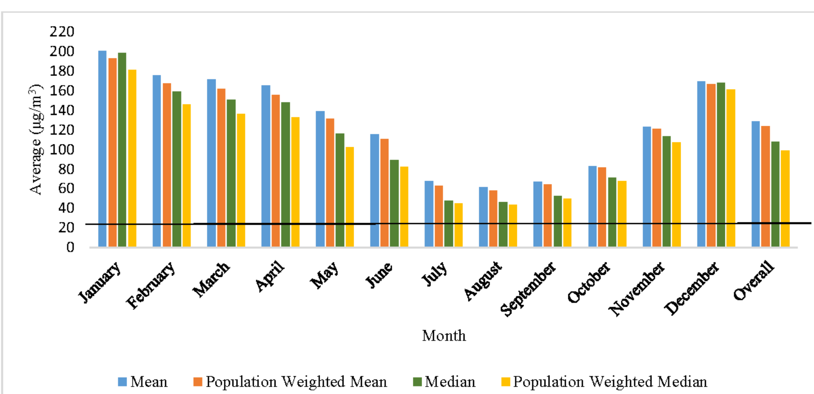


Figure S3 Hourly PM10 average (2016–2020) in Kathmandu valley (see online version for colours)



It is to be noted that the horizontal lines in the above figures indicate the WHO annual guideline value for PM_{10}.

Figure S4 Ratio of $PM_{2.5}$ and PM_{10} (December 2016–August 2020) (see online version for colours)