Science of the Total Environment

Economic and Health Burden Associated with the Ambient Air Pollution in Bangladesh Over the Last Decade (2008-2019)

--Manuscript Draft--

Manuscript Number:	STOTEN-D-22-06433
Article Type:	Research Paper
Section/Category:	
Keywords:	ambient air pollution; long-term exposure; health burden; economic burden; cardiovascular and respiratory diseases
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Abstract:	Exposure to high levels of air pollutants (PM2.5, PM10, CO, O3, NO2, and SO2) has serious negative health and economic consequences, notably in a heavily polluted country like Bangladesh. The Health and economic burden attributed to air pollutants in the eight administrative divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) of Bangladesh have been estimated for the last decade (2008-2019). Reanalysis products from the Copernicus Atmosphere Monitoring Service (CAMS) were validated and utilized for this study. Exposure-response function based on the concentration, exposed population, incidence rate of health outcomes, threshold values were regarded to estimate the health burden. Value of statistical life (VSL) and cost of illness (COI) methods were utilized to quantify the economic burden on national Gross Domestic Products (GDP). Yearly premature all-cause mortality due to ambient air pollution was estimated to be 0.80 ± 0.23 million where the contribution of cardiovascular (CVD) and respiratory diseases was approximately 51.71% and 21.58%. PM2.5, PM10, CO, O3, NO2, and SO2 each accounted for approximately 59.29%, 9.20%, 4.61%, 14.71%, 4.01%, and 8.19% of all-cause premature mortality, respectively. Yearly ~12.59 million hospitalizations were attributed to CVD and respiratory diseases. The annual economic burden of these health outcomes was estimated to be 12.11 ± 7.45 billion dollars, which equaled 6.26 ± 1.64% of the national GDP during this period. Among the divisions, the majority (5.19 ± 1.43% of GDP) of the national economic burden was attributed to Dhaka. According to this study, minimizing ambient air pollution, particularly PM2.5, in Dhaka may save the government of Bangladesh a significant amount of GDP.
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March 20, 2022

Editor

Science of the Total Environemnt

ELSEVIER Ltd.,

Subject: New manuscript submission

Dear Editor,

We are submitting a new manuscript on "**Economic and Health Burden Associated with the Ambient Air Pollution in Bangladesh Over the Last Decade (2008-2019)**" by Abdus Salam, Md Riad Sarkar Pavel, Shahid Uz Zaman, Khaled Shaifullah Joy, Nazmul Haque, Farah Jeba, Juwel Rana to Science of the Total Environemnt.

Bangladesh is a Southeast Asian country which is one of the worst victims of severe air pollution. Bangladesh has recored the highest concentration of $PM_{2.5}$ (77.1 μgm^{-3}) among the Asian countries in 2020, and it was the top most country for the last three years consequtively. Both local and transboundary air pollution are responsible for this extreme level of pollution. However, the country lacks adequate research activities regarding health and economic costs associated with ambient air pollutants.

With that keep in mind, we have performed a decadal analysis to estimate economic and health burden associated with criteria air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) in all the administrative divisions which would be the first of this kind in Bangladesh.

Our study suggests that if $PM_{2.5}$ pollution could be reduced, Bangladesh might save a significant amount of GDP per year and vehicle and industrial emissions may be the best places to start reducing air pollution. Our findings might be beneficial in establishing mitigation plans with relation to health and economic benefit in the developing nation.

The authors declare that the contents of the paper were not published before or submitted for publication in any other journal. Authors of this article do not have any conflicting interest.

We are looking forward to hearing from you.

Regards

Abdus Salam, PhD
On behalf of the authors
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Economic and Health Burden Associated with the Ambient Air Pollution in Bangladesh Over the Last Decade (2008-2019)

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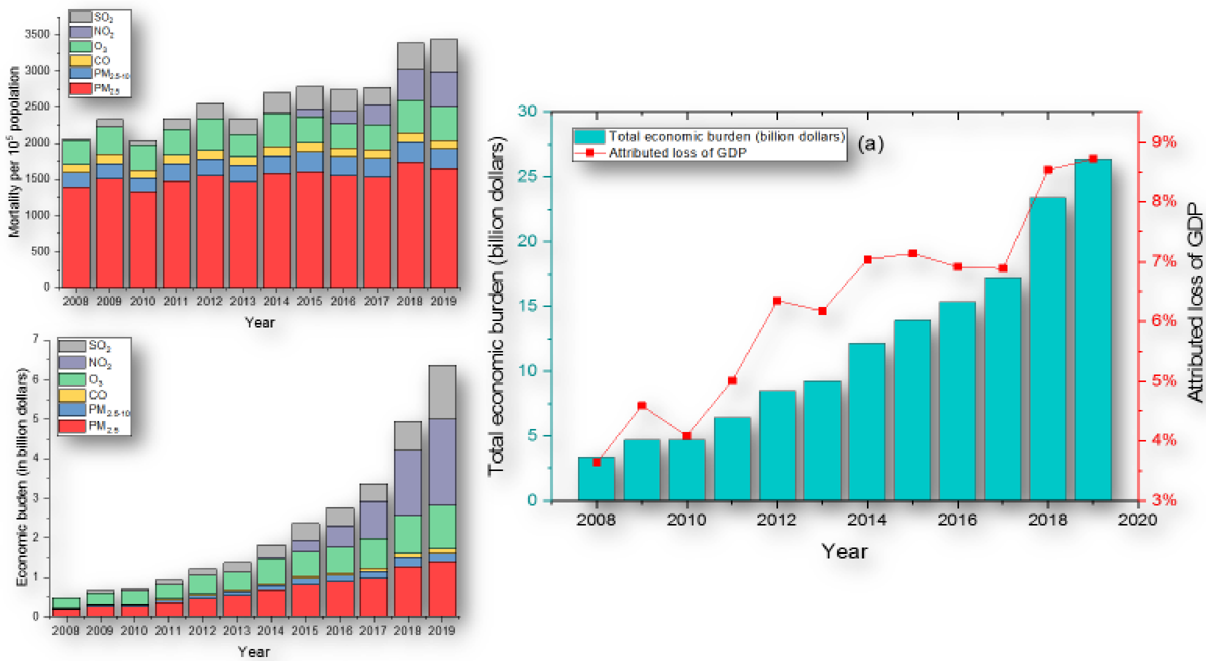
Submitted to

Science of the Total Environment

March 20, 2022

Graphical abstract



Highlights

- Annual all-cause premature mortality of 0.80 ± 0.23 million owing to ambient air pollution.
- Cardiovascular and respiratory illnesses comprised 51.71 % and 21.58 % of total mortality, respectively.
- ~6.26 ± 1.64% (12.11 ± 7.45 billion dollars) of the national GDP is lost every year.
- Dhaka alone bears a 5.19 ± 1.43% loss of the GDP among the eight divisions

Abstract

Exposure to high levels of air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) has serious negative health and economic consequences, notably in a heavily polluted country like Bangladesh. The Health and economic burden attributed to air pollutants in the eight administrative divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) of Bangladesh have been estimated for the last decade (2008-2019). Reanalysis products from the Copernicus Atmosphere Monitoring Service (CAMS) were validated and utilized for this study. Exposure-response function based on the concentration, exposed population, incidence rate of health outcomes, threshold values were regarded to estimate the health burden. Value of statistical life (VSL) and cost of illness (COI) methods were utilized to quantify the economic burden on national Gross Domestic Products (GDP). Yearly premature all-cause mortality due to ambient air pollution was estimated to be 0.80 ± 0.23 million where the contribution of cardiovascular (CVD) and respiratory diseases was approximately 51.71% and 21.58%. $PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2 each accounted for approximately 59.29%, 9.20%, 4.61%, 14.71%, 4.01%, and 8.19% of all-cause premature mortality, respectively. Yearly ~12.59 million hospitalizations were attributed to CVD and respiratory diseases. The annual economic burden of these health outcomes was estimated to be 12.11 ± 7.45 billion dollars, which equaled 6.26 ± 1.64% of the national GDP during this period. Among the divisions, the majority (5.19 ± 1.43% of GDP) of the national economic burden was attributed to Dhaka. According to this study, minimizing ambient air pollution, particularly $PM_{2.5}$, in Dhaka may save the government of Bangladesh a significant amount of GDP.

Keywords: ambient air pollution; long-term exposure; health burden; economic burden; cardiovascular and respiratory diseases

1. Introduction

A well-known cause of a wide spectrum of morbidities and premature death is ambient air pollution. The majority of this mortality and morbidities are caused by criterion pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), and sulfur dioxide (SO_2) (Borge et al., 2014). Air pollution is the second leading cause of death and disability in South Asia, accounting for between 13% and 21.7 % of all mortality and 58 million disability-adjusted life years (DALYs) due to non-communicable diseases (NCDs) like chronic and acute respiratory and cardiovascular diseases (CVD) (Krishna et al., 2017).

The health effects of $PM_{2.5}$ have been so noticeable in Asian megacities that the issue has lately been dubbed "airpocalypse," a phrase that refers to polluted air in smog-stricken areas (Maji et al., 2017). According to Pandey et al. (2021) air pollution was responsible for ~1.67 million fatalities in India in 2019, accounting for ~17.8% of the country's total mortality. Bu et al. (2021) reported that $PM_{2.5}$ has comparatively large disease burdens and accounted 6.5% of China's GDP annually from 2000 to 2010 and 8.5% of India's GDP in 2013.

CO also raises the risk of being affected by NCDs like CVD, respiratory diseases, etc. In China, even low-level CO resulted in a significant number of CVD hospitalizations, hospital stays, and hospitalization costs. Short- and long-term exposure to ozone at thresholds below regulatory levels has been related to an increased risk of death from respiratory and cardiovascular diseases, according to new data (Ryffel et al., 2019). Increases in PM_{10}, O_3, NO_2, and SO_2 were linked to increased risk of CVD and respiratory hospitalizations (Phung et al., 2016) while exposure to elevated levels of these pollutants can increase all-cause premature mortality (Ghanbari Ghozikali et al., 2016).

Bangladesh's ambient air quality is among the worst in the world and it is confronting a public health crisis that needs immediate action, as air pollution is the country's primary cause of disease and disability (Wendling et al., 2020). The annual concentration of ambient air pollutants is on the rise in the last decade (Pavel et al., 2021a). The poor air quality of Bangladeshi cities is bound to have a similar effect on GDP as has been demonstrated by Pandey et al. (2021) in the case of India. According to China Team, Bangladesh loses an estimated $6.5 billion due to air pollution-related expenditures (Bu et al., 2021).

In its 7th Five-Year Plan (2016–2020), the Government of Bangladesh (GoB) acknowledged ambient air pollution as a vital environmental issue and aimed at reducing urban $PM_{2.5}$ from 78 $\mu g\ m^{-3}$ in 2013 to 73 $\mu g\ m^{-3}$ in 2020. If the GoB manages to reduce and attain the national and consequently global threshold values of the criteria pollutants, a huge amount of economic burden will be saved.

However, studies regarding health and economic costs associated with ambient air pollutants have been scarce for Bangladesh. This study aims to estimate the health and economic burden associated with the six criteria pollutants $PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2 based on the value of statistical life (VSL) and cost of illness (COI) method through exposure-response function in the eight administrative divisions in Bangladesh. All-cause premature mortality, CVD mortality, respiratory disease mortality, CVD hospitalizations, and respiratory disease hospitalizations will be the health outcomes to estimate the burden. The national loss of GDP associated with ambient air pollution will be quantified to estimate how much economical advent would be available if we could reduce the levels of the abovementioned criteria pollutants. Furthermore, pollutant-specific economic burden will help to choose the appropriate mitigation policies in terms of health and economic gain.

2. Materials and method

2.1. Air quality and population data

Bangladesh is a low-lying, riverine country in Southeast Asia, located at the northeastern extremity of the Indo-Gangetic Plain (IGP). This study focuses on the eight administrative divisions of Bangladesh, namely Dhaka, Barishal, Chattogram, Khulna, Mymensingh, Rajshahi, Rangpur, Sylhet (Figure 1). Monthly air quality data of the six criteria pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) have been retrieved from the EAC4 (ECMWF Atmospheric Composition Reanalysis 4) global reanalysis dataset developed by European Centre for Medium-Range Weather Forecasts (ECMWF) from the Copernicus Atmosphere Monitoring Service (CAMS) for the period from January 2008 to December 2019. The dataset contains gridded global data with 0.75° x 0.75° horizontal resolution has the following vertical coverage: Surface, total column, model levels, and pressure levels. Further details about the documentation and validation have been enumerated by (Pavel et al., 2021a) Ground-based observations of these air pollutants have been mainly focused on Dhaka, the heart of the country. Such pollutants' data for the other divisions have been scarce. The reanalysis data is capable of filling the void of this unavailability of air quality data. Divisional population data were collected from the portal of World Bank (WB), DataBank (data.worldbank.org). The statistics on divisional geography, area, population, and meteorology are depicted in Table 1.

Table 1: Demographic and meteorology of the eight administrative divisions in Bangladesh.

Division	Area (sq. kilometers)	Geographical location	Population (million)	Maximum temperature (° C)	Minimum temperature (° C)	Yearly rainfall (mm)
Barishal	13295	22° 41' N, 90° 21' E	8.17	30.6	21.3	175
Chattogram	33904	22° 21' N, 91° 47' E	29.15	30.3	21.7	243
Dhaka	31051	23° 51' N, 90° 24' E	46.73	30.7	21.8	177
Khulna	22285	22° 54' N, 89° 14' E	15.56	31.2	21.7	150
Mymensingh	10552	24° 45' N, 90° 24' E	11.44	29.8	20.9	194
Rajshahi	18154	25° 00' N, 89° 00' E	18.49	31.2	20.5	121
Rangpur	16374	25° 44' N, 89° 14' E	15.79	29.5	20.1	192
Sylhet	12558	24° 53' N, 91° 52' E	9.81	30.0	19.6	344

Source: Bangladesh Statistical Yearbook, 2019.

2.2. Incidence rate of the yearly cause-specific health outcomes

"All-cause mortality," "CVD mortality," "respiratory disease mortality," "CVD hospitalizations," and "respiratory disease hospitalizations" were the selected health outcomes in this investigation. The division-wise annual mortality rates were not available. As a result, mortality rates were assumed to be equal in all divisions based on data from Bangladesh's Statistical Yearbook, 2019 (www.bbs.gov.bd). The annual incidence rate for the selected health outcomes, namely all-cause mortality, CVD mortality, respiratory disease mortality, CVD hospitalizations, and respiratory disease hospitalizations rates were 5700, 2600, 900, 27500, 16300 per 10^5 populations. These statistics were collected and accumulated by the *Directorate General of Health Services* (*DGHS*), Bangladesh. The DGHS comprises 739 hospitals, all of which contribute significantly to Bangladesh's healthcare.

2.3. Health burden associated with air pollutants

The log-linear exposure-response function was used to calculate the health burden associated with short-term air pollution exposure (Madaniyazi et al., 2016, 2015; Yao et al., 2020). The health outcome estimates in this paper are based on Yao et al. (2020) approach. The health burden was estimated in the following way for each health endpoint:

$$HB_{i,j} = BO_j \times P \times CRF_{i,j} \times (C_i - C_{Oi}) \quad (1)$$

BOj is the daily baseline incidence rate of health endpoint j, and EP is the exposure population, where HBi,j represents the health burden j related to air pollutant i and BOj is the daily baseline incidence rate of health endpoint j. Ci is the daily concentration of air pollutant i, and Coi is the daily threshold concentration for air pollutant i, which is assumed as per the threshold values set by WHO in our study (Burnett et al., 2014; Jindal, 2007; Madaniyazi et al., 2016, 2015).

The exposure-response function (CRFi,j) for health endpoint j exposed to air pollutant i calculated from the log-linear function, is an estimate of the percentage change in yearly health burden owing to a change in annual pollutant concentration (Δx) (Equation 2). Current epidemiological researches were used to determine CRF values for particular health endpoints(Lu et al., 2015; Yao et al., 2020) (Table S1).

$$CRF_{i,j} = e^{\beta,\Delta x} - 1 \quad (2)$$

Where β is the slope of the regression coefficient for a particular pollutant concentration.

2.4. Economic burden associated with health effects of air pollutants

The monetization of mortality is based on non-market valuing approaches, such as revealed or expressed preference procedures, in the absence of a market for human life (Bateman et al., 2002; Viscusi and Aldy, 2003). Creating a hypothetical market for the mortality risk under investigation and eliciting individuals' willingness to pay (WTP) to lower the chance of dying is a typical approach for assessing the monetary worth of a negative impact, such as a rise in air contaminant concentration (Braathen et al., 2010). The Value of Statistical Life (VSL) and Cost of Illness (COI) were employed in this work to quantify the economic cost of air pollutants, as these are the most well-established and frequently used metrics for monetizing mortality risks related to air pollution (OECD, 2012). The VSL is the marginal rate of substitution between wealth and mortality risk over a short timeframe, such as a year. Due to a lack of data at the divisional level, the VSL and COI for the country were calculated and utilized for the respective divisions.

The VSLs were calculated for the years 2008-2019 using the formula below(OECD, 2012) which accounts for cross-sectional income disparities before 2019.

$$VSL_y = VSL_b \times (\frac{G_{a,2005}}{G_{2005}})^{\beta} \times (1 + \%\Delta P + \%\Delta Y)^{\beta} \quad (3)$$

VSL_y is the adjusted VSL for Bangladesh in year y (=2008-2019); VSL_b is the VSL base value for Bangladesh in 2005(Mahmud et al., 2019), $G_{a,2005}$ is the GDP per capita in PPP (purchasing power parity) terms in Bangladesh in 2005; G_{2005} is the GDP per capita in PPP terms in non-OECD countries in 2005. β is the VSL's income elasticity equal to 0.9; %ΔP indicates price inflation; %ΔY represents income growth after 2005. The income elasticity of 0.9 (0.8-1.0) was suggested by (Masterman and Viscusi, 2018; Viscusi and Masterman, 2017) for low-income countries.

Equation (4), on the other hand, was used to calculate the COI for cardiovascular and respiratory illness hospitalization per case (Lu et al., 2016):

$$COI_j = COH_j + DGDP \times T_j \quad (4)$$

where COH_j is the average medical treatment cost for disease j in each instance, DGDP is the GDP per capita per day, T_j is the average labor time lost owing to disease j in each case, and COI_j is the average cost of illness and hospitalization for disease j in each case. The Health Bulletin 2019 by DGHS reports that the medical cost of hospitalization for CVD and respiratory disease is 100 dollars and 300 dollars, respectively; and the labor time lost due to CVD and respiratory disease hospital admissions amounted to 9.51 days and 7.71 days for all divisions, respectively. Bangladesh's Statistical Yearbook, 2019 provided the uniform daily average of per capita GDP for all divisions.

In the case of a health endpoint j, the economic burden ($EB_{i,j}$) of exposure to an air pollutant i may be determined by multiplying the projected number of deaths or hospitalizations ($n_{i,j}$) related to that pollutant by the VSL or COI value. For mortality and hospitalization attributed loss equations (4) and (5) are utilized, respectively.

$$EB_{i,j} = n_{i,j} \times VSL_y \quad (5)$$

$$EB_{i,j} = n_{i,j} \times COI \quad (6)$$

3. Results

3.1. Ambient air pollutants' concentrations

The ambient air pollutants had yearly average concentrations as shown in Table 2 in the eight administrative divisions in 2008-2019 while Figure 2 depicts the annual concentrations spatially of the divisions. PM concentrations were highest in Rajshahi in the studied years. Dhaka, Mymensingh, Rangpur, Khulna also showed much higher PM values than the WHO and

National standards. CO concentrations followed similar trends as PM in all the divisions. O_3 concentration was highest in Dhaka while all the other divisions showed concentrations of ~50-60 µg m^{-3}. NO_2 concentrations were below the WHO standard in all the divisions except Dhaka and Rajshahi whereas Chattogram showed very low levels among the divisions. Similarly, SO_2 concentrations did not exceed the guidance limit in the divisions except Dhaka and Rajshahi.

Table 2: Yearly average concentrations of the ambient air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) for the period 2008-2019 in the eight administrative divisions in Bangladesh.

Division	$PM_{2.5}$ (µg m^{-3})	PM_{10} (µg m^{-3})	CO (mg m^{-3})	O_3 (µg m^{-3})	NO_2 (µg m^{-3})	SO_2 (µg m^{-3})
Barishal	62.92 ±4.23	88.23 ± 5.85	0.58 ± 0.03	68.37 ± 3.38	10.41 ± 1.36	6.53 ± 0.86
Chattogram	49.03 ± 4.31	68.50 ± 5.88	0.50 ± 0.04	65.07 ± 4.78	4.85 ± 0.45	3.36 ± 0.36
Dhaka	93.33 ± 6.40	130.86 ± 8.73	0.83 ± 0.05	101.40 ± 3.62	29.92 ± 3.89	25.78 ± 3.34
Khulna	84.41 ± 4.54	118.47 ± 6.29	0.79 ± 0.04	64.28 ± 2.54	15.24 ± 1.71	11.06 ± 1.04
Mymensingh	90.46 ± 6.38	126.79 ± 8.86	0.83 ± 0.05	57.51 ± 2.13	16.32 ± 2.25	9.91 ± 1.40
Rajshahi	111.92 ± 6.51	157.02 ± 9.09	0.99 ± 0.05	62.35 ± 1.98	23.61 ± 2.06	23.09 ± 1.50
Rangpur	89.77 ± 6.13	125.77 ± 8.55	0.88 ± 0.05	59.41 ± 1.91	15.48 ± 1.96	8.65 ± 1.18
Sylhet	64.75 ± 4.45	90.62 ± 6.14	0.71 ± 0.04	52.99 ± 2.41	12.14 ± 1.59	6.89 ± 0.89

3.2. Mortality and morbidity attributable to ambient air pollution

Premature mortality attributed to $PM_{2.5}$ was highest among the pollutants over the years. Figure 3 shows the spatial distributions, whereas Figure 4 shows the mortality trend and contribution of each pollutant per 10^5 people in Bangladesh. $PM_{2.5}$, $PM_{2.5\text{-}10}$, CO, O_3, NO_2, and SO_2-related mortality were approximately 1530 ± 440, 240 ± 130, 120 ± 30, 380 ± 340, 125 ± 180, and 230 ±

100 per 10^5 populations in Bangladesh in the studied period. The contribution of $PM_{2.5}$, $PM_{2.5-10}$, CO, and O_3-related mortality to total air pollution-related mortality decreased from 67.43%, 9.80%, 5.23%, and 16.04% in 2008 to 48.16%, 7.58%, 4.61%, and 13.39% in 2019, respectively. However, the contribution of NO_2 and SO_2-related mortality to total air pollution-related premature mortality in Bangladesh rose drastically from 0.60% and 1.52% in 2008 to 14.21% and 12.95% in 2019, respectively (Figure 4(b)). Among $PM_{2.5}$, $PM_{2.5-10}$, CO, O_3, NO_2, and SO_2-related premature mortalities, CVD was responsible for 51%, 70.70%, 57.67%, 50.32%, 44.73%, and 34.79% while respiratory diseases were responsible for 22%, 30%, 13.40%, 19.08%, 18.96%, and 22.12% of those casualties, respectively. CVD and respiratory hospitalizations due to $PM_{2.5}$, $PM_{2.5-10}$, CO, O_3, NO_2, and SO_2 were 14280 ± 4110, 2320 ± 1500, 1090 ± 70, 11750 ± 10600, 290 ± 213, and 730 ± 140, respectively, per 10^5 populations in Bangladesh during 2008-2019. Rajshahi was the most affected division in terms of $PM_{2.5}$, $PM_{2.5-10}$, and CO-related casualties and hospitalizations while Chattogram was the least affected division. However, in terms of O_3, NO_2, and SO_2, Dhaka emerged as the most affected division (Figure 3). More statistics on divisional mortality and hospitalizations have been depicted in Table S2.

3.3. Economic burden attributable to ambient air pollution

The economic burden trend attributed to specific pollutants, the trend of the percent contribution of each division, and the national economic burden throughout the studied period have been depicted in Figure 5 to quantify the contribution and pattern of the economic burden against the national GDP. On the other hand, the average yearly economic burden in the eight divisions of Bangladesh for the period 2008-2019 has been depicted spatially in Figure 6. $PM_{2.5}$, $PM_{2.5-10}$, CO, O_3, NO_2, and SO_2-attributed yearly loss due to mortality and morbidity was 5.43 ± 3.21, 0.88 ± 0.56, 0.41 ± 0.24, 3.95 ± 1.94, 0.47 ± 0.74, and 0.97 ± 0.85 billion dollars which accounted for 5.43 ± 3.21%, 0.45 ± 0.13%, 0.22 ± 0.05%, 0.18 ± 0.26%, and 0.45 ± 0.27% respectively of GDP during 2008-2019. Dhaka contributed most among the divisions in terms of the yearly loss due to mortality and morbidity (Figure 5 and 6). Dhaka's yearly contribution to the national air pollution attributed to the loss of GDP was 5.19 ± 1.43%. Chattogram was second in terms of contribution attributed to $PM_{2.5}$, CO, and O_3. Chattogram costed yearly GDP loss of 0.43 ± 0.11% due to air pollution. Rajshahi contributed to economic loss significantly due to PMs, CO, O_3, and SO_2 exposure. Rajshahi's yearly contribution to the national air pollution attributed to the loss of GDP was 0.20 ± 0.04%. Khulna came next in terms of yearly economic loss with 0.18 ± 0.02% of national GDP. The contribution of three divisions namely, Mymensingh, Rangpur, and Sylhet, were equal (0.07 ± 0.02%) in terms of total mortality and morbidity. Lastly, Barishal was the lowest contributor among the divisions with a 0.05 ± 0.01% share of the economic burden to GDP.

The national economic burden increased by a factor of ~8 (US$3.33 billion and $26.38 billion) comparing the starting and the ending years of the studied period 2008-2019. Whereas GDP's share lost due to air pollution-related mortality and morbidity increased from 3.64% to 8.74% in 2008-2019 (Figure 5).

4. Discussion

Higher pollution levels in Dhaka can be attributed to higher anthropogenic activities as well as the wintertime effect of pollutants from the IGP region. (Pavel et al., 2021a) reported that the $PM_{2.5}$ and PM_{10} levels in Dhaka surpassed national air quality guidelines by about 6.0 and 2.5

times, respectively, while exceeding WHO standards by 9.0 and 6.0 times (Gupta et al., 2020). also reported high ground-level annual mean concentration of $PM_{2.5}$ and PM_{10} (76.34 ± 34.12 µg m^{-3} and 136.25 ± 68.94 µg m^{-3}, respectively) during 2013–2018 in urban sites in Bangladesh. Ground-level O_3 pollution has been on a steep increasing trend in Dhaka for the past decade and Pavel et al. (2021b) opined that NO_x emissions could be behind such elevation while Sikder et al. (2013) reported that CO, NO_x, and SO_2 are highly associated with surface O_3, suggesting the overall impact of anthropogenic emissions. The vehicular and industrial emissions can be mostly attributed to higher NO_2 and SO_2 values in Dhaka (Pavel et al., 2021a). In the case of Rajshahi, higher concentrations can be attributed to a local worsening of ambient air as well as the influence of transboundary pollution from nearby developed cities in West Bengal and the long-range transport of polluted air from the Indo-Gangetic Plain to Bangladesh due to its geographical location (Rana et al., 2016; Zaman et al., 2021).

$PM_{2.5}$-related premature mortality and morbidity were highest among the pollutants suggesting that mitigating $PM_{2.5}$ pollutions is of utmost importance. $PM_{2.5\text{-}10}$-related premature mortality was considerably lower than $PM_{2.5}$-related mortality across the years (Figures 3 and 4). In Dhaka, the annual health impact from in-vehicle $PM_{2.5}$ exposures were estimated to be 2.46 (2.28–2.63) fatalities per 100,000 automobile commuters (Kumar et al., 2021). Per 10-µg m^{-3} rise in $PM_{2.5}$ and PM_{10}, significant correlations between increased risk of CVD emergency department visits, hospitalizations, and fatalities were verified in Dhaka, Bangladesh recently (Rahman et al., 2021). Khan et al. (2019) also found a significant effect of $PM_{2.5}$ after 2–4 days of exposure when they investigated the daily frequency of emergency department visits at a Dhaka CVD hospital. CO was responsible for 22.2% of China's national premature mortality in 2017(Yao et al., 2020), while CO-related premature mortality in Bangladesh has been relatively low in contrast to other pollutants in recent years. Ozone-related casualties are also very high which suggests increasing ozone pollution, especially in Dhaka. According to L et al. (2017), rising surface ozone levels increased the risk of COPD hospitalizations and the number of cardiovascular and respiratory fatalities in India. The log-linear model predicted national O_3-related death to be ~74233, whereas the linear model projected overall O_3-related mortality to be ~69536 in China (Maji et al., 2019). Until 2013, NO_2 was not associated with premature deaths. However, during the following several years of investigation, this scenario dramatically altered. In China, He et al. (2020) found that intermediate-term NO_2 exposure had larger impact estimates on respiratory mortality than short-term NO_2 exposure, albeit the differences were not statistically significant. NO_2 caused considerably more casualties in Dhaka than in the other divisions (Figure 3). SO_2 levels of more than 10 μgm^{-3} were shown to be responsible for 1.7 % of all deaths, 3.4 % of cardiovascular deaths, and 2% of respiratory deaths (Khaniabadi et al., 2017). Premature mortality related to SO_2 was nearly as high as that ascribed to O_3 and grew significantly in the study period's last years of this study. All the pollutants had a rising pattern in case of total economic loss and contribution to the national economic loss but NO_2 and SO_2-attributed burden was rising very steeply over the last few years of the study.

Dhaka and Chattogram make up the majority of contributions since they are the economic and commercial hubs of Bangladesh, as well as the most populous divisions (Figure 5 and 6). Whereas Rajshahi might be affected by the transboundary pollution being adjacent to West Bengal. The other divisions' contribution is far smaller than Dhaka because almost all the economic, industrial activities have made it one of the most polluted in the world as described in Section 3.1. Further details about the divisional economic burden have been depicted in Table S3.

$PM_{2.5}$ and ozone pollution, respectively, may cost 2.0% and 0.09% GDP losses in 2030 if not controlled, but the advantages of reducing ambient air pollution would be enormous throughout China (Xie et al., 2019). Similarly, Bangladesh suffers loss mostly due to $PM_{2.5}$ and ozone pollution among the pollutants and could benefit greatly through their reduction. NO_2 was responsible for 28.9% of China's national premature mortality, which is much greater than in Bangladesh (Yao et al., 2020). But the contribution of NO_2 and SO_2 is increasing rapidly suggesting the need of implementing regulations on vehicles and industries immediately. Premature death and disease as a result of air pollution cost India an estimated US$288 billion and $80 billion in economic losses, respectively. This $368 billion loss accounted for 13.6% of India's GDP (Pandey et al., 2021). Likewise, air pollution is consuming roughly 8.74% of Bangladesh's GDP, which is a major subject of concern.

Nevertheless, further research should be done utilizing division-specific health outcome incidence rates for each pollutant to further acquire an understanding as to how mitigation strategies might lessen the air pollution burden in Bangladesh. Because division-specific incidence rates from national health data are still difficult to come by, this study relied on uniform health outcome rates across the country, which can lead to non-differential result misclassification. Similarly, this research was unable to create gender and age-specific distributions. Furthermore, the risk factors for each pollutant are not established for Bangladesh, which is another complication to precisely determining the impacts of individual pollutants. Besides, this study might potentially be skewed by co-pollutant effects and multiple comparison issues, resulting in a misleading positive relationship between air pollutants and health outcomes.

5. Conclusion

Bangladesh is one of the most polluted countries in the world in terms of ambient air, and Dhaka is one of the most polluted cities in the world. Polluted air has a huge impact on public health, mostly through non-communicable diseases such as cardiovascular (CVD) and respiratory illnesses. For the period 2008-2019, this study uses the EAC4 (ECMWF Atmospheric Composition Reanalysis 4) global reanalysis dataset from the Copernicus Atmosphere Monitoring Service (CAMS), which was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The health and economic losses in Bangladesh were estimated using six criterion pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) in eight administrative divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet). The annual premature all-cause number of deaths attributable to ambient air pollution was estimated to be 0.80 ± 0.23 million, with CVD and respiratory illnesses accounting for about 51.71% and 21.58%, respectively. For the past few years, the percentage contribution of NO_2 and SO_2 to total premature death has surged, whereas the contribution of other pollutants has lessened. The national economic burden increased by a factor of ~8 (US$3.33 billion and $26.38 billion) comparing the starting and the ending years of the studied period 2008-2019. The annual economic burden of these health outcomes was projected to be $12.11 ± $7.45 billion, or ~6.26 ± 1.64% of national GDP over this period. Between 2008 and 2019, the percentage of GDP lost owing to air pollution-related mortality and morbidity grew from 3.64 % to 8.74 %. Dhaka contributed 5.19 ± 1.43% GDP loss caused by air pollution per year. Chattogram, Rajshahi, Khulna, Mymensingh, Rangpur, Sylhet, and Barishal have significantly lower contributions than Dhaka.

According to this study, if ambient air pollution, particularly $PM_{2.5}$ pollutions, could be reduced, Bangladesh might save a significant amount of GDP per year. Furthermore, ozone pollution plays a substantial role in this loss, with contributions from NO_2 and SO_2 increasing at an alarming rate. These findings suggest that vehicle and industrial emissions may be the best places to start reducing pollution. On the other hand, because of its significant contribution to economic loss, the capital, Dhaka, should be at the center of this mitigation policy implementation, and countries in the IGP region should step forward to reduce the impact of transboundary pollution, which causes high levels in the country's north-western parts.

Declaration of Competing Interest:

The authors declare no conflicts of interest.

Funding:

This research has received no external funding.

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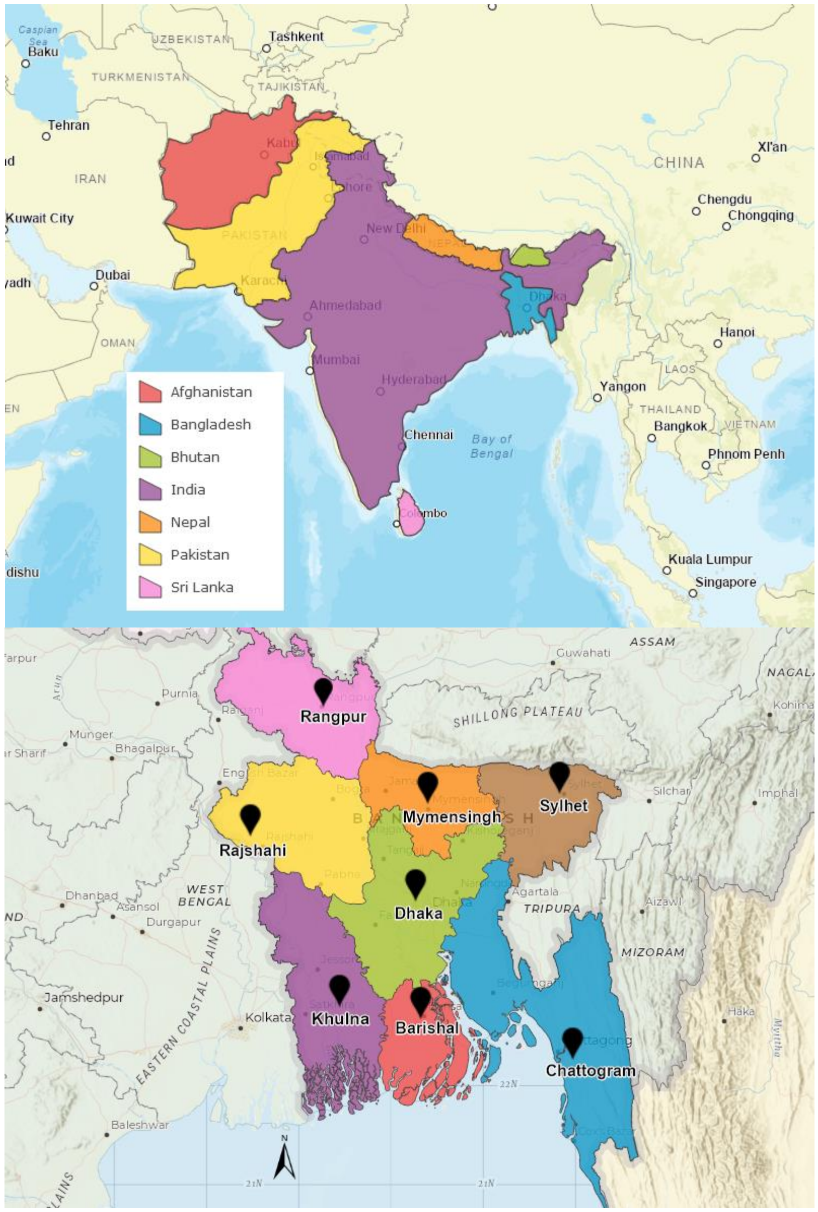

Figure 1: Position of Bangladesh in Indo-Gangetic plain region and the eight divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) in Bangladesh

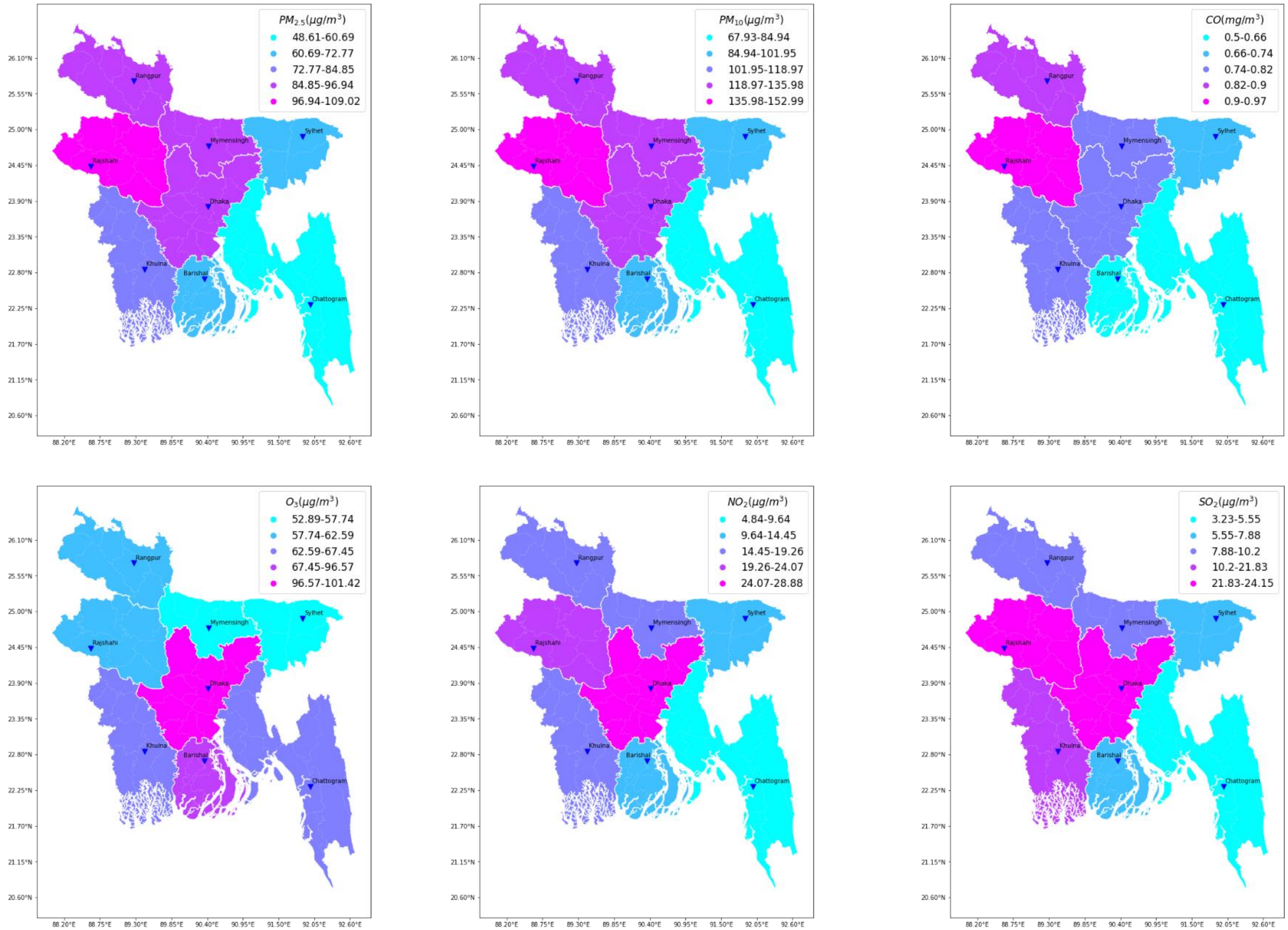

Figure 2: Ambient yearly concentrations of the criteria pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) in the eight divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) during 2008-2019.

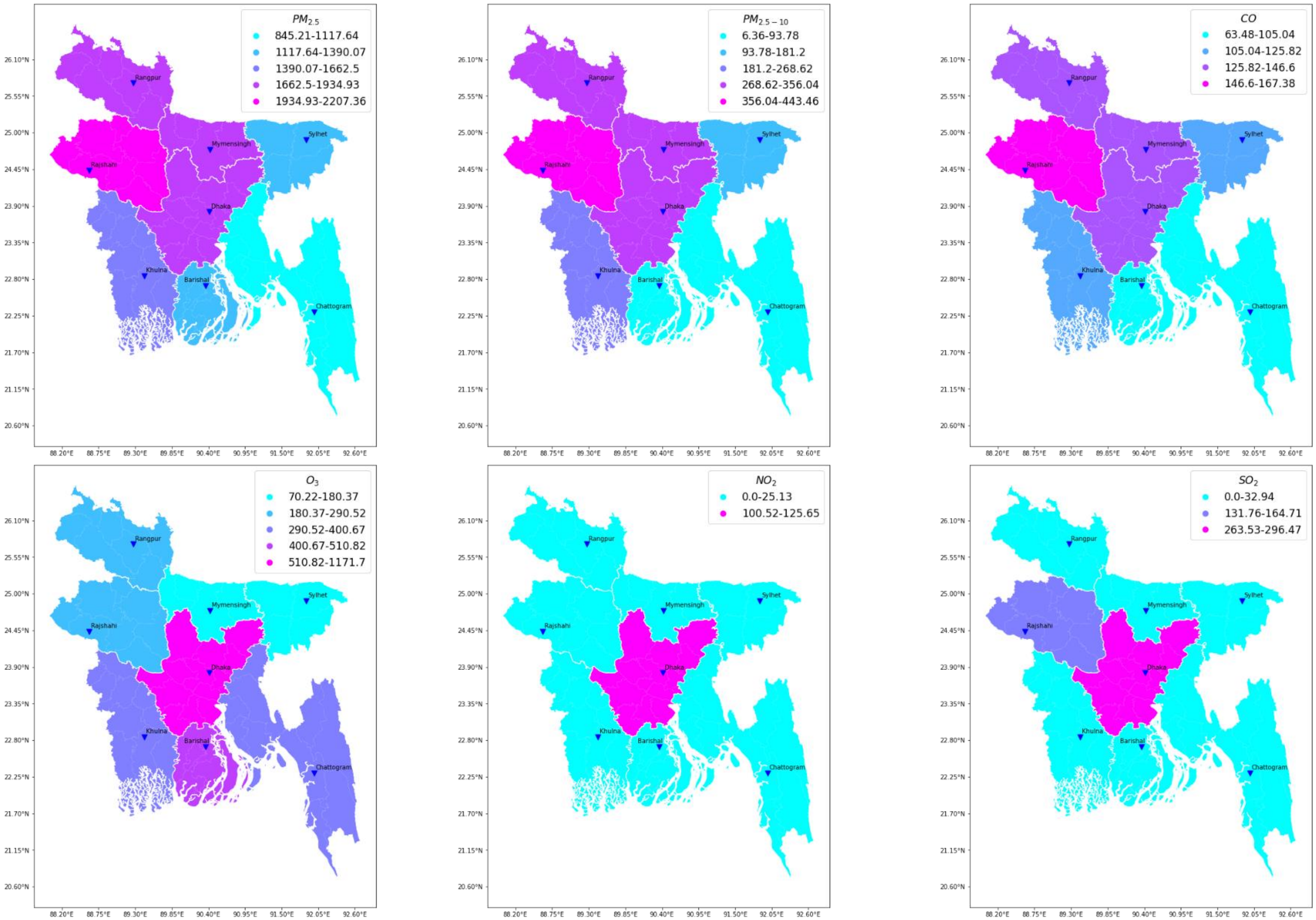

Figure 3: Health burden (yearly premature deaths per 10^5 population) attributed to the air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) for the eight divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) for 2008-2019.

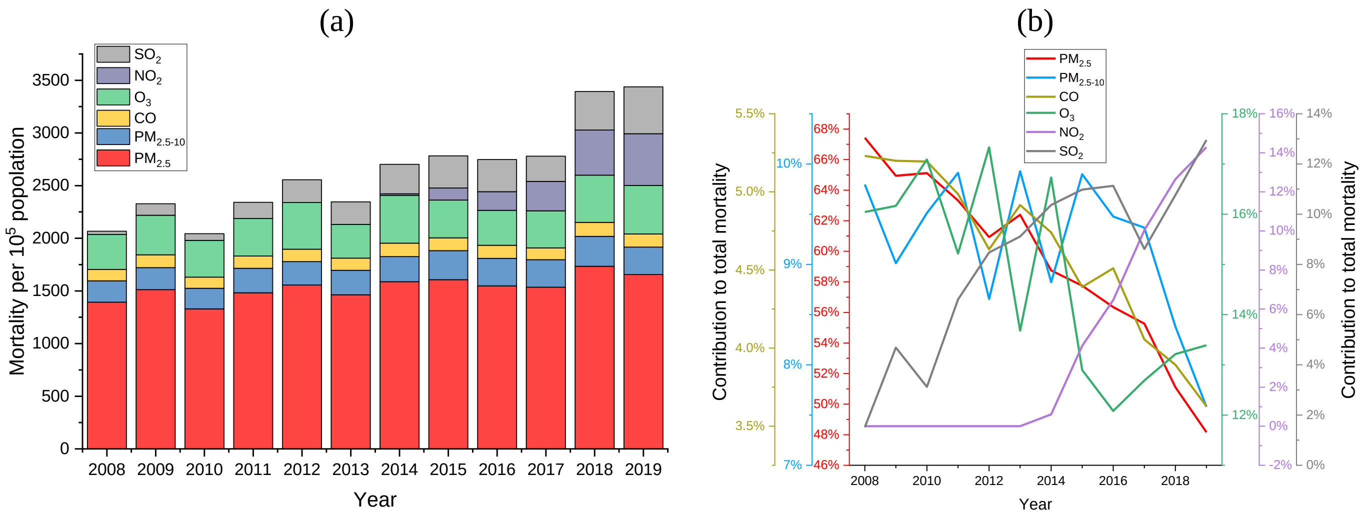

Figure 4: (a) Evolution of health burden (yearly premature deaths per 10^5 population) and (b) contribution of each pollutant to the total health burden (premature mortality due to ambient air pollution) attributed to the air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2) in Bangladesh for 2008-2019.

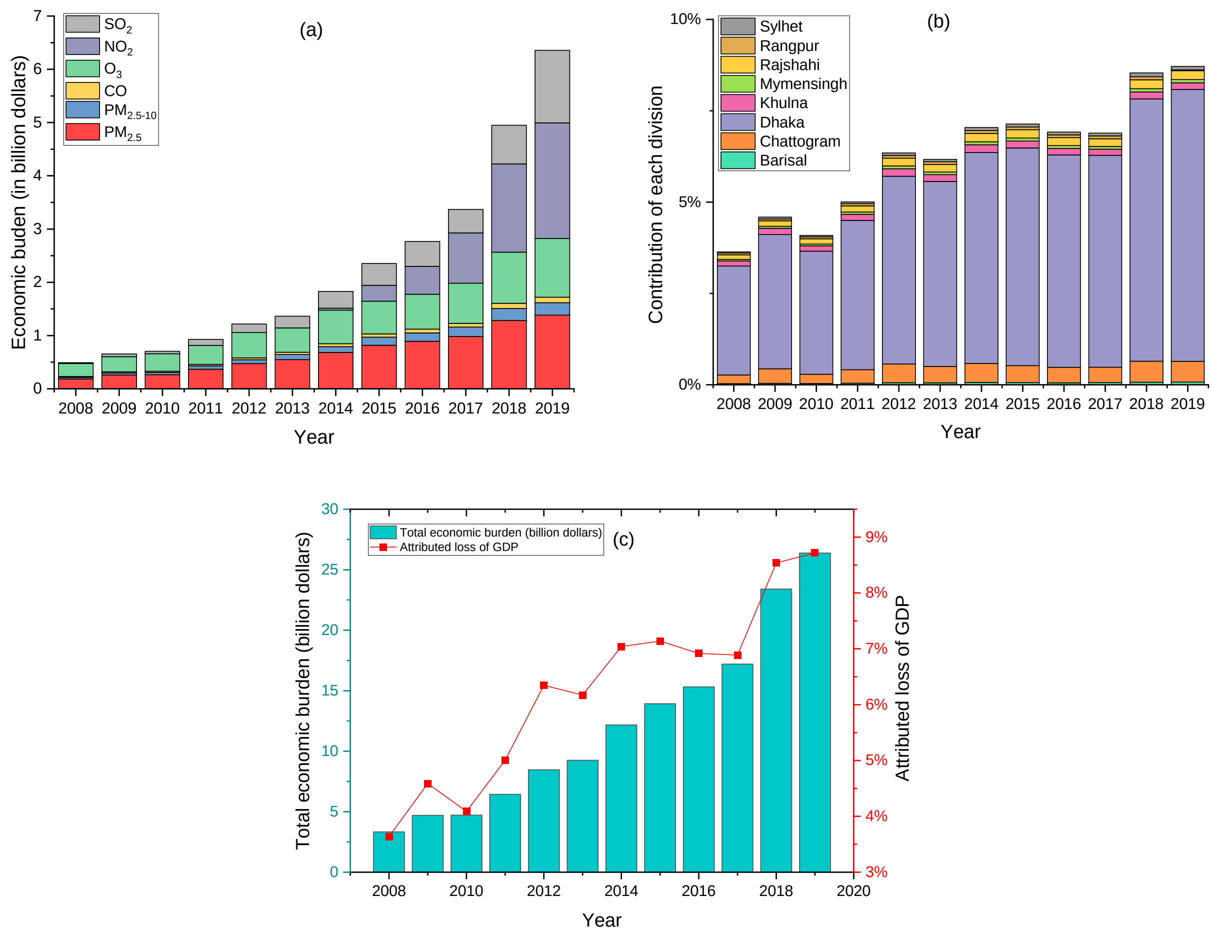

Figure 5: Evolution of (a) economic burden (yearly loss in billion dollars) attributed to the air pollutants ($PM_{2.5}$, PM_{10}, CO, O_3, NO_2, and SO_2), (b) divisional contribution to the total economic burden, and (c) total countrywide economic burden and loss of GDP in Bangladesh for 2008-2019.

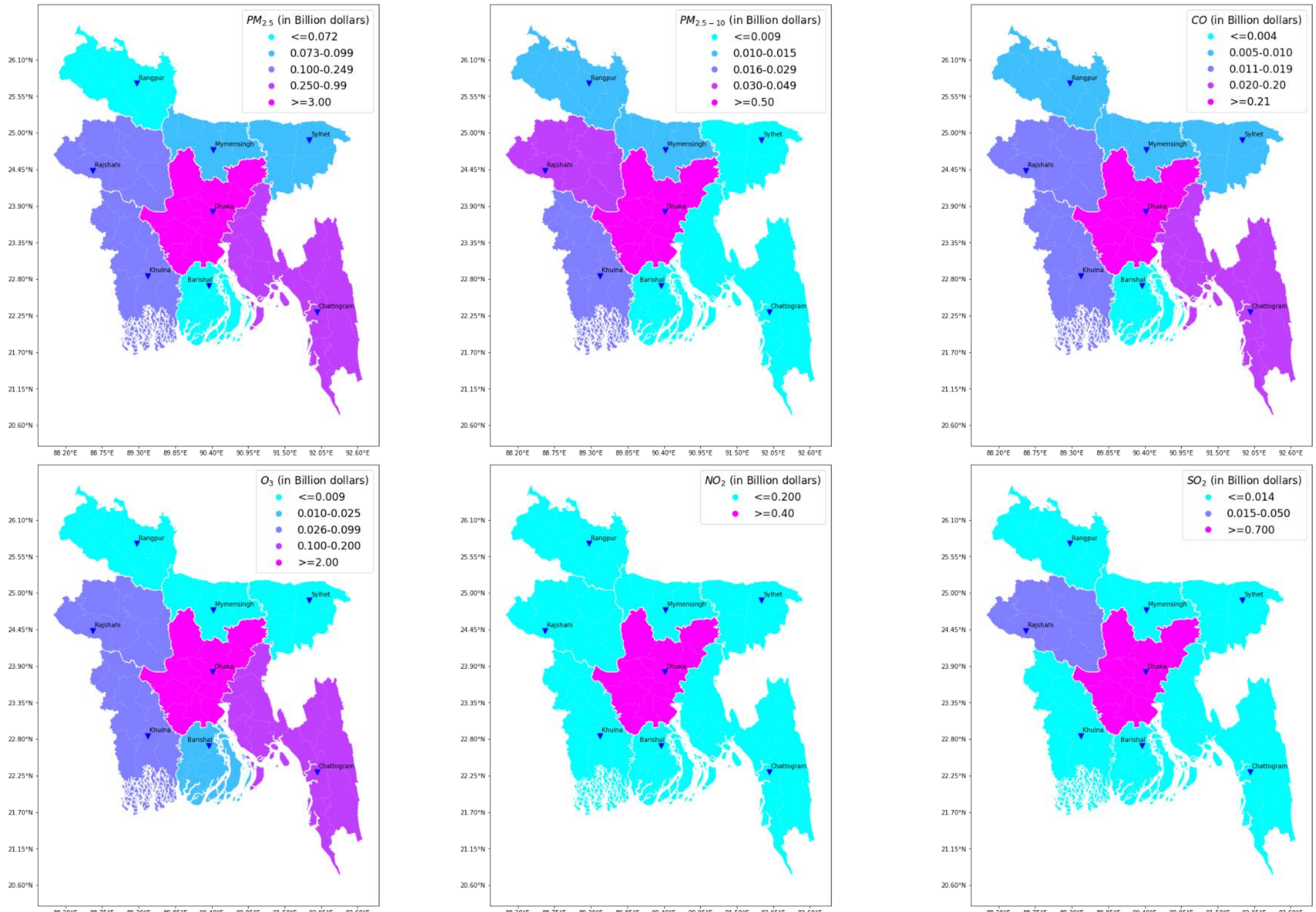

Figure 6: Economic burden (yearly loss due to premature mortality and hospitalization) attributed to the air pollutants for the eight divisions (Barishal, Chattogram, Dhaka, Khulna, Rajshahi, Rangpur, and Sylhet) for 2008-2019.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Contribution Statements:

Conception and design: AS, MRSP, SUZ, NH, KSJ

Acquisition or interpretation of data: AS, MRSP, SUZ, KSJ

Drafting of the manuscript: MRSP, SUZ, NH, KSJ

Critical revision of the manuscript for important intellectual content: All authors

Statistical analysis: MRSP, NH

Supervision: AS, FJ

Final approval of the version to be published: All authors