



Valuation of air pollution externalities: comparative assessment of economic damage and emission reduction under COVID-19 lockdown

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Abstract

Air pollution (AP) is one of the major causes of health risks as it leads to widespread morbidity and mortality each year. Its environmental impacts include acid rains, reduced visibility, but more importantly and significantly, it affects human health. The price tag of not managing AP is seen in the rise of chronic obstructive pulmonary disease (COPD), cardiovascular disease, and respiratory ailments like asthma and chronic bronchitis. But as the world battles the corona pandemic, COVID-19 lockdown has abruptly halted human activity, leading to a significant reduction in AP levels. The effect of this reduction is captured by reduced cases of morbidity and mortality associated with air pollution. The current study aims to monetarily quantify the decline in health impacts due to reduced AP levels under lockdown scenario, as against business as usual, for four cities—Delhi, London, Paris, and Wuhan. The exposure assessment with respect to pollutants like particulate matter (PM_{2.5} and PM₁₀), NO₂, and SO₂ are evaluated. Value of statistical life (VSL), cost of illness (CoI), and per capita income (PCI) for disability-adjusted life years (DALY) are used to monetize the health impacts for the year 2019 and 2020, considering the respective period of COVID-19 lockdown of four cities. The preventive benefits related to reduced AP due to lockdown is evaluated in comparison to economic damage sustained by these four cities. This helps in understanding the magnitude of actual damage and brings out a more holistic picture of the damages related to lockdown.

Keywords Air pollution · Coronavirus · COVID – 19 · Externalities · Economy · Mortality

List of abbreviations

AP	Air pollution		Severe acute respiratory syndrome coronavirus 2
COPD	Chronic obstructive pulmonary disease	WHO	World Health Organization
VSL	Value of statistical life	LERC	Linear exposure-response curve
CoI	Cost of illness	GDP	Gross domestic product
PCI	Per capita income	INR	Indian rupee
DALY	Disability-adjusted life years	USD	US dollar
SARS-CoV-2		M\$	Million USD
		B\$	Billion USD

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Introduction

The cost of development has had a major impact on the ecosystem balance. One major fallout is the jeopardized air environment (Mage et al. 1996). This is mainly due to a plethora of emission of pollutants such as PM₁₀, PM_{2.5}, NO₂, SO₂, etc. from various anthropogenic activities such as transportation, industrial processes, mining activities, waste burning, biomass burning, residential cooking, etc. (Nair et al. 2020; Gupta et al.

2020; Humbal et al. 2019; Bherwani et al. 2019; Gautam et al. 2016). Deteriorated air causes long- and short-term health effects such as chronic obstructive pulmonary disease (COPD), asthma, respiratory mortality, cancer, cardiovascular mortality, etc. (Kim et al. 2015; Ghorani-Azam et al. 2016; Maji et al. 2017; Cohen et al. 2017; Landrigan et al. 2018) among humans. This global threat is considered as one the leading cause for mortality and accounts for 7 million lives every year, estimating a total cost of more than 4% of the GDP (WHO 2020). Extensive studies have been carried out by various researchers (Gulia et al. 2015; Maji et al. 2017 & Maji et al. 2018) in heavily polluted cities to quantify the health-related monetary burden upon the exposure of human in the deteriorated air environment.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) outbreak firstly identified in Wuhan City, China (WHO 2020; Gautam and Hens 2020; Gautam and Trivedi 2020; Gautam 2020a) has now become a pandemic across the globe, resulting in about 3.5 million cases in just about 4 months (Bherwani et al. 2020; WHO 2020). The pandemic has declared global health emergency enforcing lockdown measures in activities (i.e., social contact, non-essential business, mobility, etc.) to flatten the epidemic curve. Lockdown measures have shut down industries, halted vehicular traffic, and have had a huge impact on the daily routine of the people. Due to this, considerable improvement in air quality levels of countries such as Spain (Tobias et al. 2020), India (Gautam 2020b), Brazil (Nakada and Urban 2020), and China (Sharma et al. 2020), and in cities such as Bangkok, Tokyo, Paris, and New York (He et al. 2020) has been reported. The plummet in pollutant concentration is obvious due to the restriction in anthropogenic activities.

The air quality during the lockdown period for majorly polluted cities (i.e., Delhi, Wuhan, Paris, and London) is of high significance in determining the baseline pollution level and attributable health risk, to evaluate the potential fluctuation in monetary damages. Assessment in terms of the number of lives affected is important, but a common baseline matrix such as “money” carries a much better message for the sake of understanding and decision making (Gautam 2020a). An unprecedented attempt has been made to quantify the economic benefit due to reduction in an excess number of health risk subject to mortality/morbidity attributable to lower air pollutant ($PM_{2.5}$, PM_{10} , NO_2 , and SO_2) concentration in Wuhan, Paris, London, and Delhi. Figure 1 indicates the geographical location of the cities.

The monitored ground-based pollutant concentration are compared with WHO ambient air quality guidelines (WHO 2006) to evaluate the relative risk associated with each disease and thereby, the subsequent damage cost. The economic benefit/loss is calculated for each city based on the difference in excess number of health cases attributable to pollutant concentration during the lockdown period for 2020 and 2019. The study has also

considered the overall benefit due to mass reduction in air pollutant level over the potential economic loss to the local and national government as an outcome of lockdown.

Methodology

Population (N) and air quality

Population for the years of valuation is estimated to evaluate the extent of health damages due to AP in a particular city. Population data is collected for 2019 and 2020 for calculating the number of people affected due to AP. The population of Delhi, London, Paris, and Wuhan has increased from 185, 91.8, 109.6, and 82.6 lakhs in 2019 to 195, 83.60, 93.00, and 110.2 lakhs in 2020, respectively (Economic Survey of Delhi 2019).

Lockdown is imposed in many countries due to the outbreak of COVID-19 (Wang et al. 2020a; Dutheil et al. 2020; Gautam 2020b). In Delhi, the lockdown was imposed from March 22 (Economic Times 2020), in Paris from March 18, 2020 (Jon et al. 2020), in London from March 23 (The Hindu 2020), and in Wuhan, it started from January 23. To analyze the AP levels, 31 days of lockdown is taken for the four cities and the respective data for AP as shown in Table 1 along with dates of lockdown.

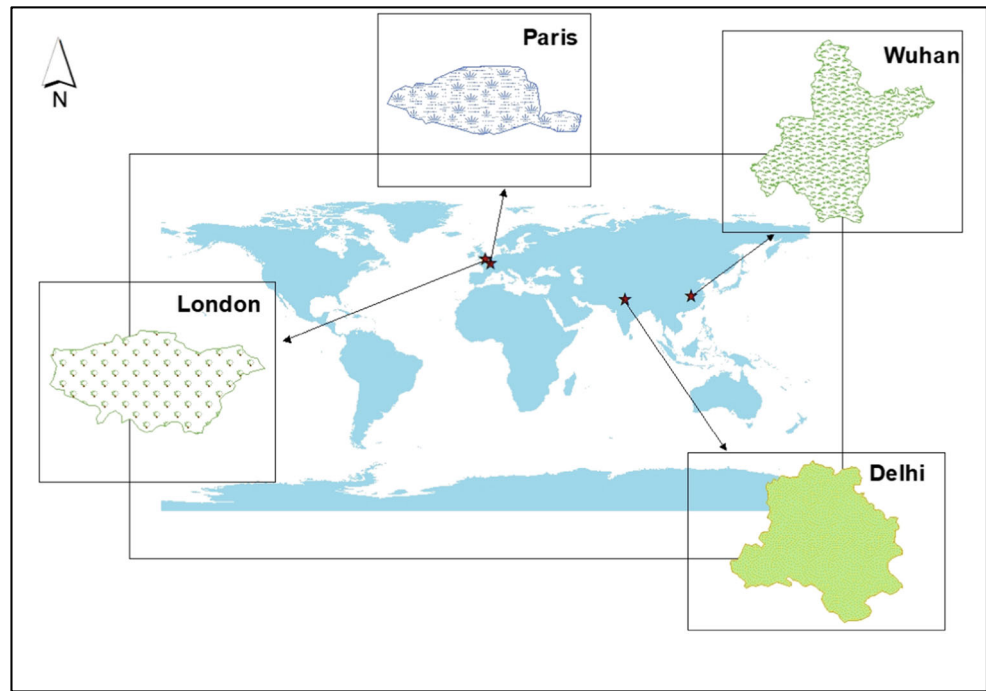
Average of 24-h mean data of $PM_{2.5}$, PM_{10} , SO_2 , and NO_2 values are taken in the period of lockdown that is 31 days for the four cities in 2020, and the same duration is taken in 2019 and values are shown in Table 1. Number of people are affected by mortality and morbidity due to the exposure of harmful pollutant concentrations by taking the 24-h mean values for 31 days for these cities is evaluated. The values of people getting affected are calculated on the basis of daily data of pollutants in comparison to daily values of WHO guidelines. The daily values are averaged for month and shown here. SO_2 has been found within limits throughout the study period for both the years.

Exposure assessment

Short-term health effects such as chronic obstructive pulmonary disease (COPD), asthma, respiratory mortality, cardiovascular mortality, and respiratory diseases due to excess pollution level during lockdown period (number of days (n) = 31) for the current and previous years were estimated using linear exposure-response curve (LERC) method.

The assessment was carried considering various factors such as relative risk $R_r(m)$ due to mean pollutant concentration, population attributable to risk (PAR) due to exposure of pollutant, baseline incidence cases (I_e) per 10^5 population corresponding to mortality/morbidity health impacts, and the total population of the city (N). Equations (1)–(3) are used for estimating earlier mentioned variables.

Fig. 1 Study area and geographical location of cities



$$Rr_m = 1 + (C_p - C_m) \times (Rr - 1) / 10 \tag{1}$$

$$PAR = \sum[\{ Rr_m - 1\}] \times \rho(c) / \sum[\{ Rr_m - 1\} \times \rho(c) + 1] \tag{2}$$

$$I_{ne} = I_e \times PAR \times N \tag{3}$$

where C_m is monitored daily ambient air concentration of pollutant “K” (daily values of average pollutant loads given in Table 1). C_p is permissible standard for the pollutant “K” (WHO Guideline values). The standards preferred are as put forth by WHO in 2006. Rr is relative risk for the pollutant “K,” and the values for R_r and I_e are discussed in Table 2. $\rho(c)$ is the proportion of population being exposed to the pollutant “K” (100% exposure is considered in our study). I_{ne} is the estimated number of cases.

Valuation of AP externalities

The monetary burden due to health risk is calculated using the methods of VSL, COI, and DALY for mortality and morbidity endpoints. For valuation, morbidity and mortality are evaluated via separate methods. The valuation of mortality is done using VSL which is usually available for each country based on assessments done for either labor wages or insurance settlements. The data on VSL is inflated to the year 2019 (which is the base year of valuation for this research) in the native currency of the reference and is compiled in Table 3.

The exchange rate/conversion factor is used for converting the native currency to USD while the inflation is carried out to bring the value to the base year of 2019. The formula for evaluation of monetary damages of mortality is given as follows:

$$(\text{Mortality})\text{Damages } (\$) = VSL \times I_{ne} \times ER \times IR \tag{4}$$

Table 1 Average ambient air quality parameters for cities during lockdown days (31 days) in 2020 and similar period in 2019 (Real-time air quality index, Delhi, London, Paris, Wuhan 2020)

City	Lockdown period in 2020	Mean PM _{2.5} (µg/m ³)		Mean PM ₁₀ (µg/m ³)		Mean NO ₂ (µg/m ³)		Mean SO ₂ (µg/m ³)	
		2020	2019	2020	2019	2020	2019	2020	2019
Delhi	March 22–April 21	82.00	130.00	51.00	123.00	With WHO Limits		With WHO Limits	
London	March 24–April 23	58.50	68.00	29.00	34.00	33.00			
Paris	March 18–April 17	51.60	70.00	29.00	43.00	36.00			
Wuhan	March 1–March 31	119.8	145.0	50.00	75.00	31.00			

Table 2 Parameters considered for mortality/morbidity (Maji et al. 2017; Maji et al. 2018)

Parameters	Mortality/morbidity	Relative risk (R_r)	Baseline incidence (I_e)
PM _{2.5}	Total mortality	1.015	543.5
	Respiratory disease	1.022	550.9
	Cardiovascular disease	1.013	546
	Asthma attack	1.021	940
	Chronic bronchitis	1.029	694
PM ₁₀	Total mortality	1.004	1013
	Cardiovascular mortality	1.006	497
	Respiratory mortality	1.008	66
	COPD morbidity	1.005	101.4
	Respiratory disease	1.004	1260
NO ₂	Cardiovascular disease	1.002	436
	Total mortality	1.024	543.5
	Cardiovascular mortality	1.021	497
	Respiratory mortality	1.037	48.4
	COPD morbidity	1.009	101.4
	Respiratory disease	1.006	1260
	Cardiovascular disease	1.010	436

where ER is the exchange rate (IMF 2020) and IR is the inflation rate (The World Bank 2019).

On similar lines to mortality, morbidity is valued using cost of illness (COI) and DALY and is added to get total morbidity-related damage assessment. The data related to DALY is taken from the WHO database and is given for the select cities in Table 4.

DALY indicates the years of life lost and thus can be valued using the annual income of an individual. The per capita income (PCI) of the selected cities with their referenced and converted values to USD (2019) is shown in Table 5. The formula related to DALY-related morbidity damage valuation is given in Eq. (5).

$$\text{Morbidity loss (DALY)}(\$) = \text{Ine} \times \text{DALY} \times \text{PCI} \times \text{IR} \times \text{ER} \quad (5)$$

Another important related to morbidity is evaluated cost of treatment of the disease, which is done using COI. COI includes total cost incurred such as medicinal cost, travel cost, hospital admission, and lost day. Cost of illness of morbidity

of each city is shown in Table 6 as compiled from the literature and converted to USD (2019). For the respiratory disease of Paris, the literature was not available, and hence, the corresponding values in London are used. Similarly, literature indicated very high costs for COPD for Wuhan, and hence, Indian costs for COPD are normalized with reference to asthma costs and used for valuation. The formula for evaluation of morbidity based on COI is given as follows:

$$(\text{Morbidity})\text{Damages (COI)} (\$) = \text{COI} \times \text{Ine} \times \text{ER} \times \text{IR} \quad (6)$$

Based on the above inputs, the valuations of morbidity- and mortality-related damages of AP are carried out and explained in the “Results and discussion” section.

COVID-19 lockdown economic damage

In order to understand the true magnitude of the damages, it is compared to economic damages sustained during the lockdown. The prevention of AP provided a benefit at the cost

Table 3 VSL for each polluted city

City	Value of statistical life (VSL)	VSL (2019) in million US dollar	Author (year)
Delhi	INR 44.69 million (2019)	0.652	Majumder and Madheswaran (2018)
London	Euro 1.83 million (2015)	2.140	Thomas (2018)
Paris	Euro 0.205 million (2004)	0.317	Monzón and Guerrero (2004)
Wuhan	RMB 3.01 million (2017)	0.455	Qu et al. (2020)

Table 4 Disability-adjusted life years (WHO 2018)

Health condition	DALY value (per capita)			
	Delhi	London	Paris	Wuhan
Respiratory disease (including COPD, bronchitis, asthma)	0.019	0.008	0.010	0.004
Cardiovascular disease	0.055	0.043	0.038	0.069

of economic damage. For this, economic damage sustained by each city during the lockdown is calculated and compiled, as shown in Table 7. The gross domestic product (GDP) of the city is compared with the GDP of the country to understand the citywide damages as literature only reported country-level damages.

Results and discussion

Ambient air quality for Delhi, London, Paris, and Wuhan cities for the lockdown month with the number of days for the years 2019 and 2020 as shown in Table 1 is considered for calculating the health damage cost due to air pollutants. During the lockdown days due to limited transportation and industrial output, air pollution is significantly reduced (Wang et al. 2020b). Some of the air pollutants came within the World Health Organization (WHO) guidelines (Jordan 2020) just a few days into the lockdown. NO₂ concentration for all the cities during the lockdown is less than the WHO limit every day, whereas breach is observed for the year 2019. Pollutant such as PM_{2.5}, PM₁₀, NO_x, and SO₂ results in various health damages such as respiratory diseases, COPD, cardiovascular diseases, and mortality. These pollutants are considered to calculate corresponding health damage cost. It can be observed that SO₂ concentration was below the acceptable permissible limit set by International guidelines (WHO 2006). Hence, no health damage due to pollutant was considered. The daily mean of PM_{2.5}, PM₁₀ and daily averages for NO₂ during the month of lockdown days in 2020 and the same month for the previous year 2019 was found beyond the acceptable limit, thereby health damage assessment is carried out by certain set of formulas (Eqs. (1)–(3)) (Maji et al. 2017).

In order to quantify the impacts in monetary terms, it is essential to understand the mechanism by which the impact happens. The impact pathway approach (Bherwani et al.

2019; Ghorani-Azam et al. 2016) reveals how emitted pollutants lead to different adverse outcomes on human wellbeing and other natural environments. In the current research, we are primarily focusing on human health impacts of AP, and the same is quantified in monetary terms. Basic parameter of the number of people affected under morbidity and mortality are calculated using Eqs. (1)–(3) using the available data. The factors for each of the pollutant parameter are taken from Table 2. The reference concentration for the pollutants is taken from the WHO guidelines. The cases of morbidity and mortality under each heading of disease for each city are summarized in Table 8.

While standard deviations have been reported in pollutant concentration, relative risks, and baseline incidences, the resolution of calculation for multiplicative parameters using standard deviation may yield complex variations in the results. Hence, the morbidity and mortality assessments have been done on average values. From Table 8, it can be seen that PM_{2.5} is the most damaging parameter affecting many people in all cities. The highest cases are reported in Delhi due to PM; however, no cases due to NO₂ in 2019. Since it has the highest number of cases to start with, the lockdown indicates the highest reduction as well. While this will hold true for monetary benefit as well or not is discussed later. Wuhan indicates the second-highest number of people affected; however, reduction in 2020 appears to be low. London and Paris show a similar size of cases. Figure 2 indicates the morbidity and mortality between the two years 2019 and 2020.

The valuation of morbidity is carried out for cardiovascular and respiratory diseases, including general respiratory ailments, asthma and COPD. COI is used to include the expenditure of treatment, including the outpatient and in-patient costs related to the ailment. The COI for each city, based on national averages, have been used for diseases, as indicated in Table 6. The valuation of the cost of treatment of morbidity is evaluated using Eq. (6). Apart from the treatment expenditure,

Table 5 Per capita income of each city

City	Per capita income (PCI)	PCI (2019) in US dollar	Author (year)
Delhi	INR 4,02,000 (2018)	6064	PRS (2019)
London	Euro 43,629 (2015)	52,027	TUC (2016)
Paris	Euro 52,100 (2017)	62,243	European Commission (2019)
Wuhan	RMB 1,35,136 (2018)	20,044	CEIC (2018)

Table 6 Cost of illness for morbidity assessment

Cities	Morbidity illness	Cost of illness as reported (year)	Cost of illness USD (2019)	Author (year)
Delhi	COPD	INR 44390 (2005)	1675	Koul et al. (2019)
	Asthma	USD 637 (2019)	637	Ghoshal et al. (2016)
	Respiratory disease	USD 637 (2019)	637	Ghoshal et al. (2016)
	Cardiovascular disease	INR 300000 (2018)	4522	Apoorva (2018)
London	COPD	GBP 1640 (2006)	3028	Starkie et al. (2008)
	Asthma	Euro 169 (2010)	240	Mukherjee et al. (2016)
	Respiratory disease	GBP 1850 (2014)	2603	Burki (2017)
	Cardiovascular disease	GBP 7600 (2015)	10,492	Bhatnagar et al. (2016)
Paris	COPD	Euro 7924 (2015)	9174	Bourbeau et al. (2019)
	Asthma	Euro 538 (2010)	663	Doz et al. (2013)
	Respiratory disease	GBP 1850 (2014)	2603	Burki (2017)
	Cardiovascular disease	Euro 4719 (2013)	5541	Tuppin et al. (2016)
Wuhan	COPD	USD 4527 (2019)	4527	(Koul et al. 2019, Li et al. 2018)
	Asthma	USD 1590 (2015)	1721	(Shan 2017)
	Respiratory disease	USD 1089 (2016)	1133	(Li et al. 2018)
	Cardiovascular disease	USD 2236 (2012)	2581	(Wang et al. 2015)

the reduction in functionality of an individual also leads to massive losses to the economy. This is often evaluated as DALY and is valued as well. For valuation, per capita income is used as a surrogate measure for the individuals getting effected along with DALYs associated with their diseases. The data related to DALY and per capita income based on city GDP averages is given in Table 4 and Table 5, respectively. The DALY-related valuation is carried out using Eq. (5). The morbidity valuation is shown in Table 9 while Fig. 3 represents a comparative loss of all cities due to AP morbidity in the years 2019 and 2020.

It can be seen from Fig. 3 that the highest benefit in terms of absolute numbers and in terms of percentage reduction of about 38% is seen by Delhi, which also happens to be one of the most polluted cities in the world. The lockdown scenario must have brought down

the pollution levels drastically bringing a huge benefit to the city. In terms of change, Paris also sees a considerable reduction with morbidity damages reduced by almost 35%. The city of Wuhan and London see a similar kind of drop in terms of percentage reduction of about 19 to 20%. While the morbidity damages are in millions of dollars, it is evident that they have reduced considerably as compared to the previous year, indicating that the lockdown has improved air quality thereby saving of millions of dollars and more importantly an improved health and associated intangibles.

Mortality valuation is done using VSL, which is usually evaluated for low- to moderate-income groups in order to avoid overshooting the valuations. The value of statistical life for individuals staying in different countries is given in Table 3 and is used for the mortality

Table 7 Economic damage cost due to lockdown in each country of these cities

City	City GDP (1) B\$ (unless otherwise mentioned)	Country GDP (2) B\$ (unless otherwise mentioned)	Ratio (3 = 1/2)	Economic loss-country (4) (B\$)	City economy loss (B\$) (5 = 4 × 3)	Author (year)
Delhi	INR 8.56 billion	INR 231 billion	00.04	00.14	05.36	The Economic Times 2020 (2020)
London	INR 8.56 billion	INR 231 billion	00.25	74.40	18.60	Office of National Statistics (2019); Matt and Martin (2020)
Paris	651.0	2470	00.26	60.00	15.81	Institut national de la statistique et des études économiques INSEE (2016); France 24 (2020)
Wuhan	00.02	13.61	0.002	320.0	00.51	Trade commissioner service (2015); Lily (2020)

Table 8 Quantification of Impacts in terms of number of people affected due to pollutants

Pollutant	Health condition	City							
		Delhi		London		Paris		Wuhan	
		2019	2020	2019	2020	2019	2020	2019	2020
PM _{2.5}	Total mortality	14,089	9063	3195	2387	3707	2396	6829	5536
	Respiratory disease	19,605	12,789	4256	3451	5335	3462	9467	7843
	Cardiovascular disease	12,511	8013	2611	2095	3258	2104	6071	4965
	Chronic bronchitis	30,620	20,218	6832	5579	8587	5593	14,728	12,312
	Asthma	32,232	20,981	7489	5643	8730	5661	15,569	12,282
PM ₁₀	Total mortality	6121	1172	28	9	40	17	934	249
	Cardiovascular mortality	4035	780	19	6	26	12	621	166
	Respiratory mortality	718	141	3	1	5	2	111	30
	COPD morbidity	692	133	3	1	5	2	106	28
	Respiratory disease	6780	1281	31	10	44	19	1032	275
NO ₂	Cardiovascular disease	1289	243	6	2	8	4	194	51
	Total mortality	0	0	168	0	206	0	106	0
	Cardiovascular mortality	0	0	131	0	158	0	78	0
	Respiratory mortality	0	0	23	0	28	0	14	0
	COPD morbidity	0	0	12	0	14	0	7	0
Respiratory disease	0	0	98	0	118	0	58	0	
	Cardiovascular disease	0	0	54	0	65	0	32	0

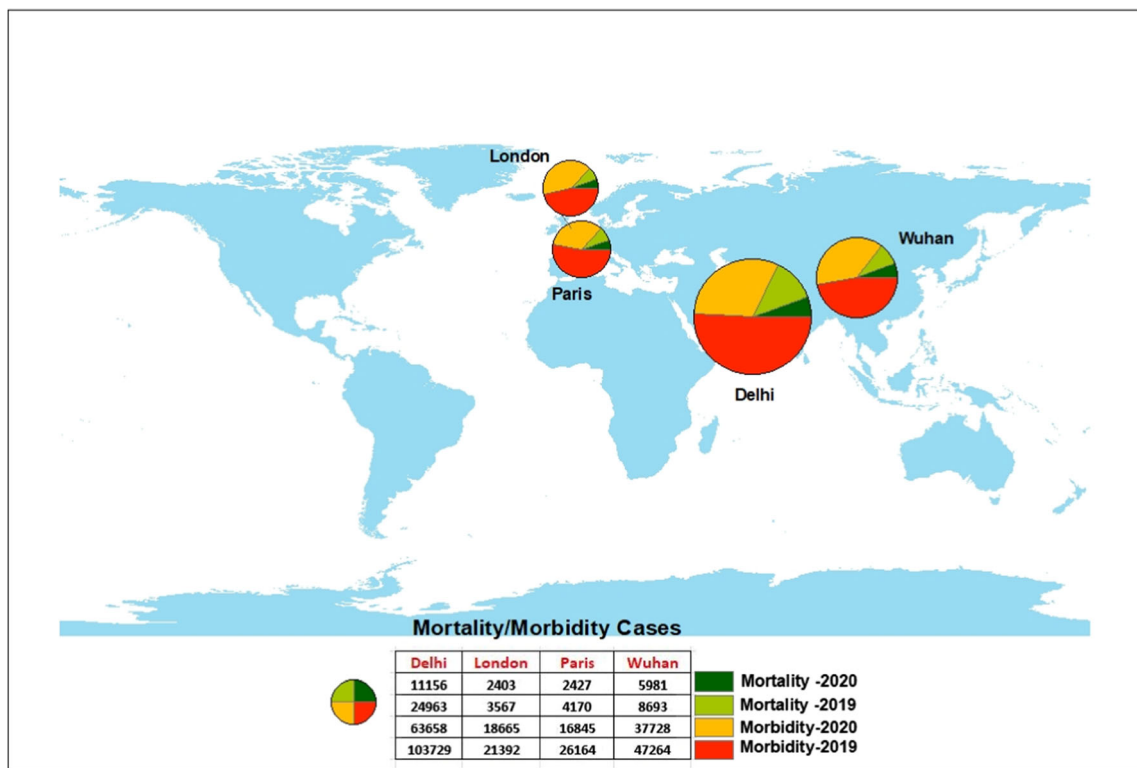


Fig. 2 Mortality and morbidity for the study period in 2020 as against 2019

cases as evaluated by the relative risk and baseline incidences reported by WHO. Table 10 gives the mortality valuation under each category of disease for the respective pollutants. The equation used for valuation for mortality damages is given in the “Methodology” section as Eq. (4). Figure 4 gives a year-wise comparison of the benefits produced by lockdown in 2020 in terms of mortality reduction.

It is to be noted that mortality damages are reported as total mortality, and within that, there is respiratory and cardiovascular mortality. The total mortalities of particulate matter and nitrogen dioxide have been added to get the total value of damage related to mortality, which then further includes mortalities related to other factors of AP. A similar result is obtained as in case of morbidity. Delhi has the greatest benefit with almost 49% reduction in damages related to mortality due to lockdown followed by Paris with 39% reduction, London with 29%, and Wuhan having 26% reduction. Further, in terms of absolute numbers, the reduction of damages is highest in Delhi, followed by London, Wuhan, and Paris, respectively.

Overall, mortality and morbidity represent the total loss due to AP in the select cities. The damages have been added and compared to the economic damages caused during the considered lockdown of these cities. The economic damages have been reported at the country level; the ratio of the GDPs of the corresponding cities is taken to normalize the damages for cities. The raw data with respect to economic damages and GDP ratios are given in Table 7. The overall damages and economic damages are shown in Table 11.

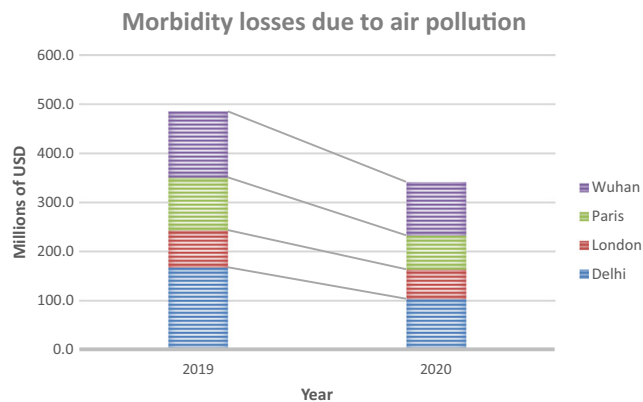


Fig. 3 Comparative morbidity losses for each city

Valuation of AP damages for 2019 and 2020 gives an understanding of the magnitude of damages which occurs due to AP. Due to lockdown, there is a drastic reduction in AP as indicated by 2020 scenario in Table 8 and Table 11, leading to the prevention of AP-related damages. It can be seen from Table 11 that the highest prevention happens in terms of absolute magnitude and percentage in Delhi. London has the second-highest amount of prevention in terms of absolute numbers but falls behind Paris in terms of percentage benefit. Wuhan has the lowest prevention in terms of magnitude and percentage.

When compared with the economic damages, as indicated in Fig. 5 above, actually Wuhan has the highest normalized benefit due to AP reduction, followed by Delhi, London, and Paris, respectively. This is evidently shown in terms of damage prevented per unit economic damage, which is highest for Wuhan 1.85, followed by Delhi 1.19, London 0.11, and Paris 0.03.

Table 9 Morbidity valuation for diseases caused by air pollutants

Health condition	Total morbidity(COI+DALY) valuation in M\$							
	Delhi		London		Paris		Wuhan	
	2019	2020	2019	2020	2019	2020	2019	2020
Respiratory disease	14.78	9.64	12.95	10.50	17.03	11.05	11.56	9.58
Cardiovascular disease	60.72	38.89	33.23	26.66	25.67	16.58	24.05	19.67
Chronic bronchitis	54.88	36.24	23.69	19.34	52.64	34.29	67.97	56.82
Asthma attack	24.30	15.82	05.09	03.83	10.93	07.09	28.16	22.22
COPD morbidity	01.24	00.24	00.01	00.00	00.05	00.02	00.49	00.13
Respiratory disease	05.11	00.97	00.09	00.03	00.14	00.06	01.26	00.34
Cardiovascular disease	06.26	01.18	00.08	00.03	00.06	00.03	00.77	00.20
COPD morbidity	00.00	00.00	00.04	00.00	00.14	00.00	00.03	00.00
Respiratory disease	00.00	00.00	00.30	00.00	00.38	00.00	00.07	00.00
Cardiovascular disease	00.00	00.00	00.42	00.00	00.51	00.00	00.13	00.00
Total	167.29	102.97	75.89	60.40	107.56	69.12	134.49	108.95

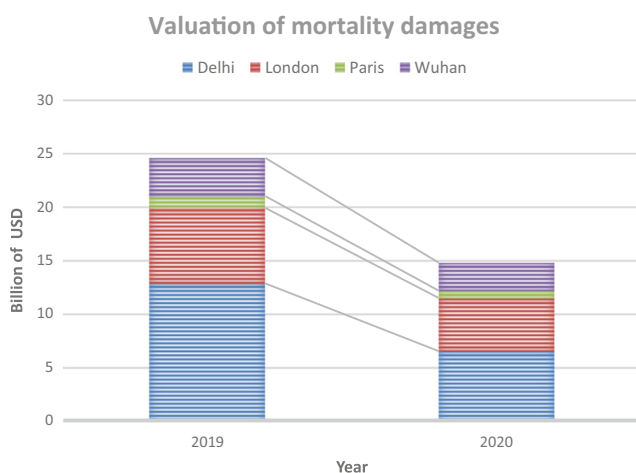
Table 10 Mortality damages with respect to pollutants and respective diseases

Pollutant	Health condition	Total mortality valuation in B\$							
		Delhi		London		Paris		Wuhan	
		2019	2020	2019	2020	2019	2020	2019	2020
PM _{2.5}	Total PM _{2.5} mortality (1)	08.94	05.75	06.66	04.97	1.04	0.67	03.11	02.52
PM ₁₀	Total PM ₁₀ mortality (2)	03.89	00.74	00.06	00.02	0.01	0.00	00.42	00.11
	Cardiovascular mortality	02.56	00.50	00.04	00.01	0.01	0.00	00.28	00.08
NO ₂	Respiratory mortality	00.46	00.09	00.01	00.00	0.00	0.00	00.05	00.01
	Total NO ₂ mortality (3)	00.00	00.00	00.35	00.00	0.06	0.00	00.05	00.00
	Cardiovascular mortality	00.00	00.00	00.27	00.00	0.04	0.00	00.04	00.00
	Respiratory mortality	00.00	00.00	00.05	00.00	0.01	0.00	00.01	00.00
Total mortality (1 + 2 + 3)		12.83	06.50	07.07	04.99	1.10	0.67	03.58	02.63

Conclusion

This study highlights that although the world is fighting with COVID-19 and suffering from huge economic losses, due to reduced cohesive situation for work, the environment is benefitted. This further is demonstrated in monetary terms for reduced health damages related to air pollution. The exposure and impact assessment is carried out for Delhi, London, Paris, and Wuhan, using relative risk and baseline indices of various air pollutants including PM_{2.5}, PM₁₀, and NO₂. The study further incorporates monetization of the impacts for 2019 and 2020, to gauge the magnitude of impact reduction of air pollution under COVID-19 lockdown scenario. The monetary assessment of damages is done using econometric approaches like VSL, CoI, and PCI for DALY. The key conclusions are summarized as follows:

1. PM_{2.5} is one of the major contributors to the burden of disease related to AP. Delhi, being one of the

**Fig. 4** Mortality damages for air pollutants for 2019 and 2020

most polluted cities globally, is the worst affected. PM₁₀ and NO₂ impacts are also considerable, while SO₂ is found within WHO guidelines limits for both 2019 and 2020. Monetarily, the impact is curtailed by average 36% in mortality and about 28% in morbidity in the year 2020 due to substantial reduction in AP amid reduced anthropogenic activities owing to COVID-19 lockdown. In terms of an absolute number of people affected, an average 31% reduction is for combined mortality and morbidity for all cities. Impacts of NO₂ are zeroed for the year 2020. For PM_{2.5} mortality cases, Delhi sees the highest fall in the number of cases for 2020 from 2019, followed by Paris, Wuhan, and London, in that order.

2. Morbidity damages estimated using CoI and PCI for DALY indicates that exposure impact is highest for Delhi followed by Wuhan, Paris, and London for 2019, reporting damages worth 167.3 M\$ (million USD, 2019), 134.5 M\$, 107.6 M\$, and 75.9 M\$, respectively. A major reduction in morbidity damages is seen in Delhi in 2020 because of lockdown, revealing reduction of damages worth 64.3 M\$, with Paris falling in second place with 38.4 M\$ worth of reduction, trailed by Wuhan and London at 25.5 M\$ and 15.5 M\$ reductions respectively. This indicates that lockdown has affected cities differently, indicating there are potentially other factors like geographic location, background concentration, seasonality, and meteorological parameters playing a major role in alleviating the damages.
3. While morbidity damages are in millions of dollars, the mortality damages extend that to multiple order of magnitudes. The 2019 estimates suggest that the absolute mortality damages are highest for Delhi at 12.8 billion USD (B\$, 2019) and achieved a maximum reduction of 49% in 2020 lockdown. The

Table 11 Consolidated results in comparison to economic damage for cities

City	Days (a)	2019 AP damage (B\$) (1)	2020 AP damage (B\$) (2)	Prevention due to lockdown (B\$) (3 = 1–2)	Percentage reduction in 2020 (%) (100 × 3/1)	B\$ prevented/day (3/a)	Economic damage due to lockdown (B\$) (4)	AP damage prevented per unit economic damage (5 = 3/(–4))
Delhi	31	13.00	06.60	06.40	49%	00.21	– 05.36	01.19
London	31	07.14	05.05	02.09	29%	00.07	– 18.60	00.11
Paris	31	01.21	00.74	00.47	39%	00.02	– 15.81	00.03
Wuhan	31	03.71	02.74	00.97	26%	00.03	– 00.53	01.85

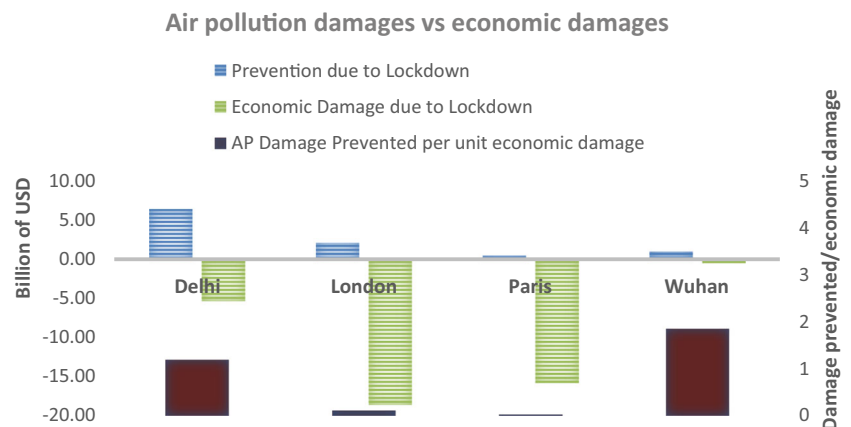
damages in London are recorded as second highest at 7 B\$; however, the recovery is second lowest at 29%, second to Wuhan having recovery of 26%. Wuhan suffered damage of 3.5 B\$ in 2019 and 2.6 B\$ in 2020. Paris had the lowest damages of 1.1 B\$ in 2019 and made a reduction of about 39% in 2020. It can be seen the trend in mortality damages between the cities is not similar to morbidity, indicating that there could be other compounding factors like age, life expectancy, and standard of living in these cities.

- The total of morbidity and mortality damages reduction in 2020 is compared with the economic damages being reported for the cities. It is reported that London (18.6B\$) suffered maximum economic damage during its respective lockdown days, while Wuhan suffered the lowest (0.56B\$). Paris (15.81B\$) and Delhi (5.36B\$) suffered the second-highest and lowest damages, respectively. Delhi, London, Wuhan, and Paris prevented AP damages worth 6.4B\$, 2.09B\$, 0.97B\$, and 0.47 B\$, respectively, in 2020. This indicates that Wuhan and Delhi could extract better worth from prevention of damages from lockdown as compared to their lockdown losses. This might be due to the fact that both these cities are highly polluted as compared to Paris and London and are economically developing as well. Wuhan is actually higher as the economic

damages incurred by that city are the lowest. The lowest recovery is made by Paris, while London stands at second-lowest.

It is apparent that while quantifying AP damages in terms of exposure and affected population is fruitful, there are more insights which can be explored to understand the true magnitude of the damage caused by it. The monetary evaluation gives a common denomination for comparison and for making a rational decision for policy formulation. The above research of four major global cities demonstrates that while the world is suffering from enormous economic damage, the lockdown has created some positive for the air environment and hence the human health as well. While the above analysis might hold true for the majority of the cities suffering from a probable of AP, a detailed analysis should be carried out for the respective city before making decisions. Accounting of the cost and benefits due to halting of anthropogenic activities gives us a clear indication of the change of damage being incurred on the ecosystem and on human health. It further suggests that stronger policies are needed to safeguard the ecosystem balance.

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Fig. 5 AP damage prevented due to lockdown in comparison to economic damage

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