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Estimating health and economic burden of PM₁₀ pollution in Agra, India using AirQ+ and VSL approaches

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Air pollution affects both the environment and the economy. This study aimed to analyse the annual and seasonal concentrations of respirable suspended particulate matter (PM₁₀) and evaluate the monetary loss from health risk caused by PM₁₀ in Agra, India, for the year 2022. PM₁₀ levels were monitored using ground-based methods. Health impacts were estimated via the AirQ+ model. Seasonal trends were analyzed using Mann-Kendall and Sen's slope tests, and economic costs were calculated using the Value of a Statistical Life (VSL) approach. Post-monsoon had the highest seasonal concentration, followed by winter, summer, and monsoon. Proportions of attributable exposure to PM₁₀ were estimated to be 41.91% for post-neonatal all-cause mortality, 65.6% for bronchitis in children, 78.4% for chronic bronchitis, 65.65% for lung cancer, 79.2% for respiratory diseases, and 55.38% for ischemic heart disease (IHD) in adults. We observed significant ($p < 0.05$) decreasing trends in summer and an increasing trend in post-monsoon. The annual economic burden was estimated at US\$ 95.56 per person, US\$ 202.58 million for Agra, and extrapolated US\$ 135.40 billion for India. The expense amount is approximately 4% of the gross domestic product (GDP), 46% of all tax revenues, and around 130% of the healthcare budget of India. The study underscores the urgent need for pollution control to safeguard health and ease the heavy economic burden locally and nationally.

Keywords PM₁₀, AirQ+ v.2.1.1 model, Back-trajectory model, Mann-Kendall test & sen's slope, Value of a statistical life

India is the fifth-largest economy in the world (US\$ 3.7 trillion)¹ with 6.9% Gross Domestic Product (GDP) growth rate². Rapid economic growth drives increased demand for goods/services, and elevating resource consumption, resulting in rising pollution from sources like industries, garbage waste, along with transportation, construction, mining activities, excessive use of chemicals, burning of fossil fuels, indoor activities, agricultural activities, etc. Particulate matter (PM), ammonia, sulphur dioxide, nitrous oxide, carbon monoxide, methane, chlorofluorocarbons, and carbon dioxide are the main pollutants that increase pollution in the environment. The most common source of pollution in the environment is the discharge of harmful pollutants like ground level ozone and particulate matter³. PM₁₀ designates particles with a size of about 10 micrometres or less. These can originate from combustion, pollutants from industries, and automobile exhaust, as well as other natural and human-caused sources. These particles can be breathed in through the nose and throat and enter the lungs, leading to major health issues such as irregular heartbeats, asthma, lung disease, nonfatal heart attacks, and early death. Particulate matter concentration and geological composition are correlated, while the origins and atmospheric processing determine the geochemical composition of PM, which is a mixture of solid particles and liquid droplets in the atmosphere.

The concentration of particulate matter is lower on weekends than it is during the workdays, and it is also asserted that vehicular emissions on roads are identified as a primary local source of pollution during the period of 2006 to 2010⁴. In Sao Paulo, during the winter months, PM_{2.5}, PM₁₀, NO₂, and O₃ levels were higher than average⁵. The concentration of NO₂, SO₂, and PM₁₀ has increased from 13.43% to about 27.52% from 2002 to 2014, and the associated medical expenses have raised about US\$ 67.99 million to US\$ 254.52 million quite quickly⁶. PM₁₀ concentrations ranged from fair to poor during the winter and post-monsoon seasons⁷. Air

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pollution in India is among the highest worldwide⁸. One of the most significant problems in the world is street dust pollution in cities, which has a detrimental impact on both human health and the environment⁹.

Air pollution drives climate change, harms ecosystems, and affects economic growth. Worldwide, nine out of ten people breathe air that is highly polluted, resulting in seven million deaths annually¹⁰. Significant threats to these fragile ecosystems include pollution, habitat degradation, water shortages, and climate change. Unchecked urbanization and industrialization in the surrounding areas can result in increased pollution and encroachment, which can affect habitat availability and water quality^{11–19}. Health care expenses related to air pollution have a considerable financial impact. Some of these costs include doctors' visits, hospital stays, diagnostic tests, medications, and continuous care for chronic diseases. It has been consistently shown over the past few decades that exposure to PM_{10} pollution is associated with negative health outcomes^{20,21}. Both societal losses and medical expenses are greatly increased by the health effects of inhalable particles. Monetary valuation, or the process of translating values for non-marketable health risk into monetary units^{22,23}. With increased exposure to rising temperatures, harsh weather, deteriorating air quality, and emerging pests and diseases, climate change is increasingly posing a serious threat to public health²⁴.

The monetary cost of a number of illnesses caused by air pollution was INR 49.45 million from 2006 to 2010²⁵. In Indonesia, the total yearly cost of air pollution's negative health effects was about US\$ 2943.42 million, using local data to quantify and assess the health and economic impacts of air pollution in an area covered by five districts in the Special Capital District for 2018 and 2019²⁶. An estimated economic loss of US\$ 437 million was spent annually on medical expenses, lost productivity, early mortality, and other costs like transportation and caregivers among the exposed population groups by using a prevalence-based technique for chronic obstructive pulmonary disease (COPD), asthma, and ischemic heart disease (IHD), respectively, and new avenues for recycling rejected materials to reduce waste are provided by circular economy solutions^{27,28}. The uses of nature-based strategies to reduce air pollution noted that this might be accomplished by teaching individuals about ecological issues via value-based education²⁹.

Air pollution is not just a major worldwide issue; it also poses a serious threat to the survival of human beings at the regional and local levels. Air pollution has been measured all over the world, but the health effects of air pollution have not been explained in a vast part of the globe. There has been relatively little economic research of the health effects of particulate matter for the Indo-Gangetic Basin (IGB). Air pollution is a significant barrier to attaining the goal of sustainable development, and it is a major cause of various human health issues, leading to a fall in efficiency and productivity. It has a considerable financial burden on healthcare expenses on individuals as well as the exchequer. The IGB is one of the most highly populated regions of India, and Agra is often a highly polluted city over the IGB. It is a sensitive region of India that is responsible for a sizable portion of the premature deaths brought on by air pollution.

Objectives of this study are (i) to analyze the annual and seasonal concentrations of particulate matter (PM_{10}) from ground-based monitoring; (ii) to identify the health risks associated with air pollution (PM_{10}); and (iii) to estimate the economic losses resulting from air pollution (PM_{10}) in Agra city. This study also extrapolated rough indicative broader economic loss estimates at the national level for India. By quantifying the seasonal variations, health risks, and associated economic losses, the findings offer valuable evidence for policymakers to prioritize air quality management. The study underscores the urgent need for effective pollution control strategies to protect public health and reduce the substantial economic burden on both local and national levels.

Results

Level of concentrations of PM_{10}

The total mean mass concentration of PM_{10} was 198.52; it indicates that the magnitude of yearly average concentration in all seasons has been much higher than the standards by the World Health Organization's (WHO) recommendations $15 \mu g m^{-3}$, the Environmental Protection Agency's (USEPA) and National Ambient Air Quality Standards (NAAQS) set limits ($50 \mu g m^{-3}$, and $60 \mu g m^{-3}$). The seasonal variations in Agra's particulate matter (PM_{10}) concentrations from July to September during the monsoon, October to November during the post-monsoon, December to February during the winter, and March to June during the summer in 2022 in Fig. 1. The study area suffers with the highest concentration of PM_{10} ($253.1 \mu g m^{-3}$) during the post-monsoon season. This is followed by the winter season ($220.4 \mu g m^{-3}$), summer season ($209.9 \mu g m^{-3}$), & monsoon season ($85.0 \mu g m^{-3}$). A similar correlation could exist between increased use of coal, wood, and cow dung cakes for cooking and heating and high mass concentration during the wintertime periods, as well as a drop in the boundary layer and stable atmospheric condition (wind speed $1 m s^{-1}$). PM_{10} levels peak in the post-monsoon season, particularly due to Diwali-related fireworks and increased tourist activities, which often extend into early winter³⁰. High level of pollution may be due to the influx of tourists, a poor road and traffic system, a crowded population, a grinding storm in adjacent areas, and particulate matter emissions from Delhi, the burning of agricultural waste in Punjab and Haryana, and the downwind supply of dust storms from Rajasthan are acknowledged as regional or seasonal contributor during post-monsoon³¹. Fig. 2 presents a comparison of the air quality in different most polluted cities and countries^{32,33}. On days with greater rainfall during the monsoon, the lowest particle concentrations were observed^{34,35}. Remarkably, 99% of people on the earth lived in areas in 2019 that did not fulfill the severe air quality guidelines set by the WHO for 2021³⁶.

Table 1 presents seasonal variations (mean, standard deviation, minimum, and maximum) and trends by using Mann-Kendall (S) and Sen's slope (Q). The annual mean value was 198.5, with a range from 30.2 to 365.9, showing a significant decreasing trend ($S = -2.06$, $Q = -1.14$, $p = 0.039$). Post-monsoon recorded the highest mean concentration ($253.1 \pm 106.6 \mu g/m^3$) with a statistically significant increasing trend ($S = +2.06$, $Q = +7.69$, $p = 0.039$), indicating growing pollution levels during this period, possibly due to regional biomass burning and festive activities. Winter also showed high concentrations ($220.4 \pm 99.4 \mu g/m^3$), but with no significant decreasing trend ($S = -0.54$, $Q = -1.35$, $p = 0.591$), suggesting relatively stable levels. Summer displayed similarly

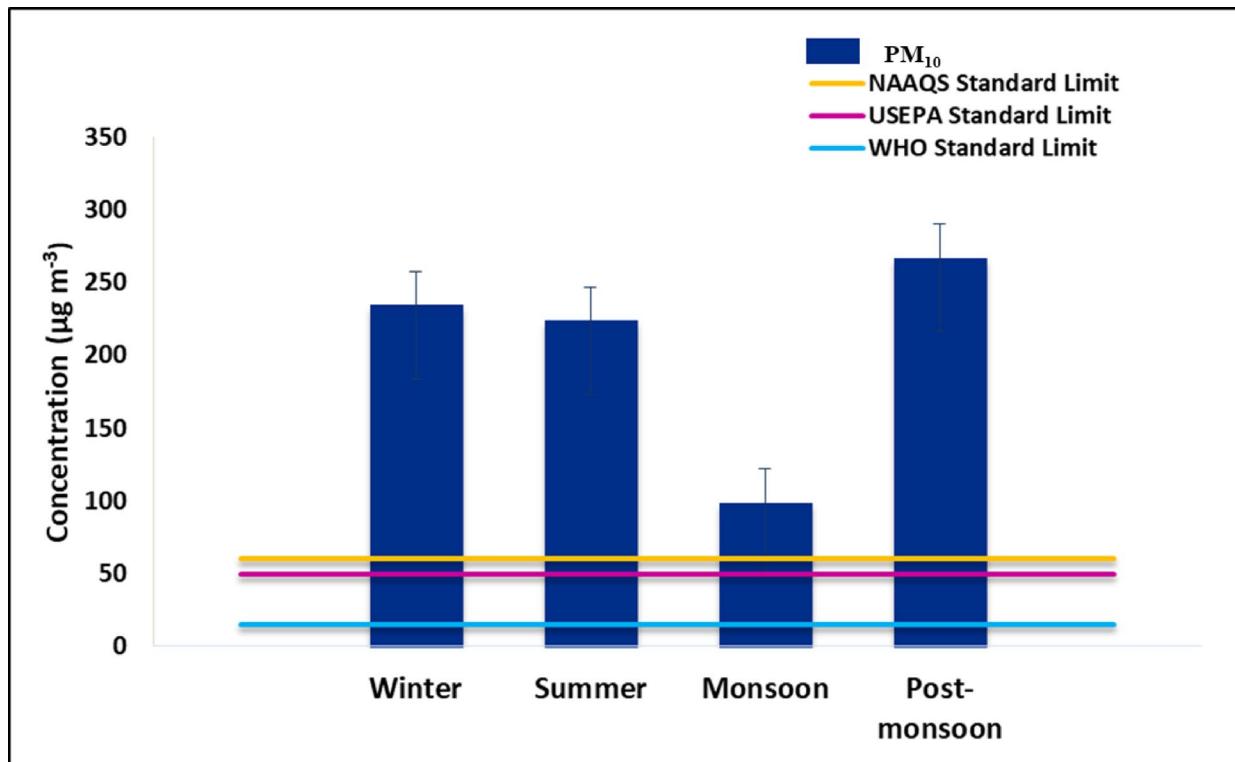


Fig. 1. Seasonal variations in PM_{10} .

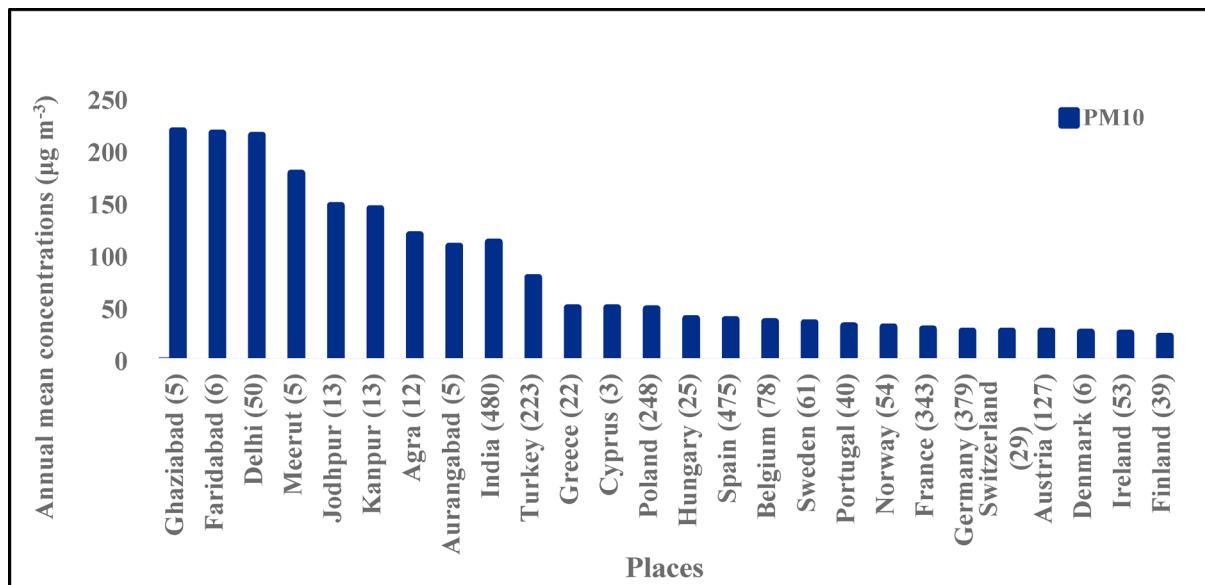


Fig. 2. Comparison of the present air quality status with different cities and countries.

elevated PM_{10} levels ($209.9 \pm 69.7 \mu\text{g/m}^3$) but with a significant decreasing trend ($S = -2.67$, $Q = -9.24$, $p = 0.008$), likely due to better atmospheric dispersion. Monsoon had the lowest mean PM_{10} ($85.0 \pm 28.6 \mu\text{g/m}^3$), with no significant increasing trend ($S = +1.24$, $Q = +1.38$, $P = 0.215$), attributed to rain-induced pollutant washout. These findings highlight post-monsoon and winter as critical periods for PM_{10} pollution, with significant temporal variations requiring targeted mitigation strategies. It is also shown the air quality index (AQI) category was unhealthy for sensitive groups in all seasons except monsoon (moderate). Table 2 represents the correlation coefficient matrix between PM_{10} and meteorological parameters such as wind speed (m s^{-1}), temperature ($^{\circ}\text{C}$), and relative humidity (%). With respect to PM_{10} , there was a negative correlation with wind speed (-0.14) and

Seasons	Mean \pm SD	Min-Max	AQI category	Event(n)	Mann-Kendal (S)	Sen's slope (Q)	P-value (CI:95%)
Annual	198.5 \pm 99.8	30.2-365.9	Unhealthy for sensitive groups	74	-2.06	-1.14	0.039
Winter	220.4 \pm 99.4	100.4-310.3	Unhealthy for sensitive groups	17	-0.54	-1.35	0.591
Summer	209.9 \pm 69.7	60.5-300.3	Unhealthy for sensitive groups	19	-2.67	-9.24	0.008
Monsoon	85.0 \pm 28.6	35.6-120.9	Moderate	20	+1.24	+1.38	0.215
Post Monsoon	253.1 \pm 106.6	30.2-365.9	Unhealthy for sensitive groups	18	+2.06	+7.69	0.039

Table 1. Annual and seasonal AQI category and Statistical analysis of PM₁₀.

Parameters	PM ₁₀	Wind speed (m/s)	Relative humidity (%)	Temperature (°C)
PM ₁₀	1.00			
Wind Speed (m/s)	-0.14	1.00		
Relative Humidity (%)	-0.57	-0.01	1.00	
Temperature (°C)	0.01	0.46	-0.33	1.00

Table 2. Pearson correlation coefficient matrix of PM₁₀ with meteorological factors.

relative humidity (-0.57) and a positive correlation with temperature (0.01). Fig. 3 represents seasonal wise PM₁₀ concentration ($\mu\text{g m}^{-3}$) along with meteorological parameters such as air temperature (AT, °C), relative humidity (RH, %), and wind speed (WS, m s^{-1}) over different sample days in 2022. PM₁₀ pollution is significantly high in post-monsoon and winter, often exceeding safe limits. Lower temperatures and low wind speeds contribute to pollutant accumulation³⁷.

Fig. 4 shows wind rose diagrams using original software to display wind coming from various directions during the winter, summer, monsoon, and post-monsoon seasons. Hourly data for every season and wind speed in meters per second were analyzed. In winter, the north, north-northeast, and west directions seemed to have the highest wind frequency; in summer, the easterly and south-easterly winds were stronger; during the monsoon season, the winds were stronger from the west-northwest and east directions; and during the post-monsoon season, the winds were stronger from the north, northeast, and west directions. The backward trajectory analysis conducted using the HYSPLIT model provides valuable insights into the transport pathways of air masses affecting Agra City (27.00°N, 78.00°W) above ground level (AGL) at 0800 UTC in the past 24 h of the second week of every month in 2022.

As shown in Fig. 5, the air parcels arriving at Agra predominantly originated from northwestern and northern regions. Back-trajectory analysis indicates long-range transport of pollutants from distant sources. The trajectories at different altitudes—green (2000 m AGL), blue (1500 m AGL), and red (500 m AGL)—showed the probable paths taken by air masses before reaching the source location. The analysis revealed that during the monsoon season, air parcels mainly originated from the southwest and south, indicating the influence of relatively cleaner maritime air, which corresponded to lower PM₁₀ concentrations. In the post-monsoon period, trajectories shifted towards the northwest and north, suggesting significant contributions from agricultural biomass burning and urban emissions from northern India. Throughout the winter months, air masses arrive from the north and northwest brought pollutants from industrialized and densely populated regions, compounded by stagnant meteorological conditions, resulting in elevated PM₁₀ levels. During the summer season, the dominant transport from the west and southwest indicated dust intrusion from arid regions like Rajasthan, contributing to high particulate matter concentrations. Thus, the backward trajectory analysis provided a comprehensive understanding of seasonal source influences on air quality in Agra.

Impact of air pollution on human health risk

Fig. 6 shows the exceedance factor, which represents the critical amount of pollution in Agra, was greater than 1.5 except during the monsoon season (0.85). Exceedance factor determined to be greater than 2.5 indicates the serious health danger of air pollution in the post-monsoon season³⁸. Significant exceedance factors may be attributable to a variety of causes, such as high population density, vehicle emissions, industrial activity, construction dust on road and building sites, and open burning of garbage and biomass. Population-weighted mean concentration is a more accurate indicator of population exposure as it considers both the level of contaminants and the distribution of people within a region. The total predicted population for the virtual cell in this study was computed to be 2.12 million people for Agra, while the population at the provided cell location was taken to represent 53,053 people for Dayalbagh³⁹. A population weighted mean concentration of 4.96 $\mu\text{g m}^{-3}$ indicates that a large amount of the emission is present in the air, raising questions about its effects on both human beings and the environment.

Table 3 shows the estimated attributable proportion (EAP%) was 78.4% (41.9–90.9%), the estimated number of cases was 12,311 (6,581–14,275), and the estimated cases per 1,00,000 at individuals' risk was 5,802 (3,101–6,727) with a relative risk factor of 1.12 (CI 95%: 1.04–1.19) for the incidence of chronic bronchitis, 79.2% (55.4–91.0%) for respiratory mortality, 55.4% (12.9–73.3%) for ischemic heart disease (IHD) mortality, 65.6% (41.9–81.6%) for lung cancer mortality, 41.9% (33.6–55.4%) for all natural causes mortality in adults age \geq 30 year. The high burden of chronic bronchitis and respiratory mortality in adults both showing strong associations with

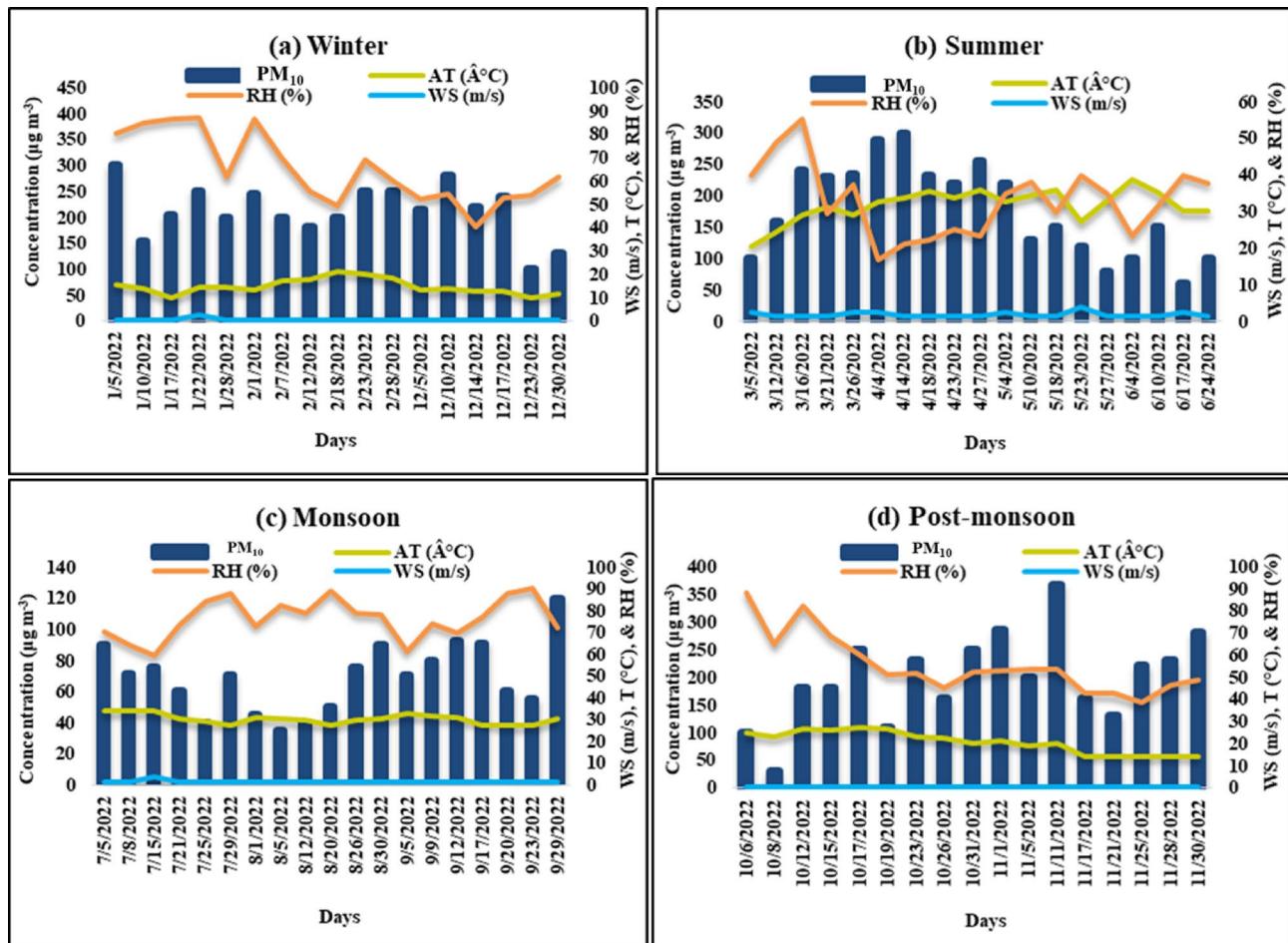


Fig. 3. Variation in PM_{10} with meteorological factors during (a) Winter (b) Summer (c) Monsoon (d) Post monsoon.

exposure ($\text{RR} > 1.1$). New-borns who died between 1 and 12 months of age are considered post-neonatal infant mortality. The predicted attributable percentage was 41.9% (23.9–60.8%), the estimated number of cases was 3,37,960 (1,93,422–4,90,450), and the projected number of incidents per 1,00,000 people who are at risk was 1,593 (912–2,311) with a risk factor of 1.04 (CI 95%: 1.02–1.07). Incidence of chronic bronchitis in children (age 1–5 years) ranged 65.6%, from (0–91.0%); estimated number of cases 10,295 (0–14,291); estimated cases per 1,00,000 people at risk 4,851 (0–6,735); and estimated risk factor 1.08 (CI 95%: 1–1.19). These data shed light on the prevalence of childhood bronchitis and the size and consequences of post-neonatal infant mortality. Children's bronchitis prevalence ranged 76.56%, from 0–96.23%^{40–49}.

Economic cost burden

VSL is the regional trade-off rate between money and fatality risk; it indicates the population's readiness to pay for increased safety as well as the additional expense of lowering health hazards. Life expectancy is 68 years⁵⁰ the average age of population is 24.7 years⁵¹ and the annual average income in Uttar Pradesh is Rs. 65,431. In 2022, the population of India was 1.417 billion⁵². The average money to spend or invest to save one human life has been estimated to be INR 7,912 (US \$95.56). The annual economic cost burden estimated is INR 1,67,734 lakh (US\$202.58 million) for the entire population of Agra and extrapolated INR 11,21,130 crore (US\$135.40 billion), approximately 4% of the GDP of India in 2022. The expense amount is estimated to be 46% of all tax revenues and around 130% of India's healthcare budget in 2022. Air pollution is the second most serious threat to health in India. Table 4 shows a comparison of the monetary expenses and health risks related to air pollution in different places; annual economic cost is estimated to be more than \$150 billion⁵³. The high rate of disease and mortality brought on by air pollution may make it more difficult for India to achieve its objective of an economy worth \$5 trillion by 2024 and its significant negative economic impact from lost output⁵⁴. The health-related economic loss caused by PM_{10} and SO_2 represented 1.63% and 2.32% of the GDP, respectively, from January 2015 to June 2015 in 74 cities of China^{55–59}.

Contaminants in the air have detrimental impacts on the nation's economy and standard of living for its people. Air pollution is interpreted to have a far more alarming economic cost (US\$ 135.40 billion), with 385.65 instances per 100,000 people in India at risk. This national economic loss estimate was extrapolated from the

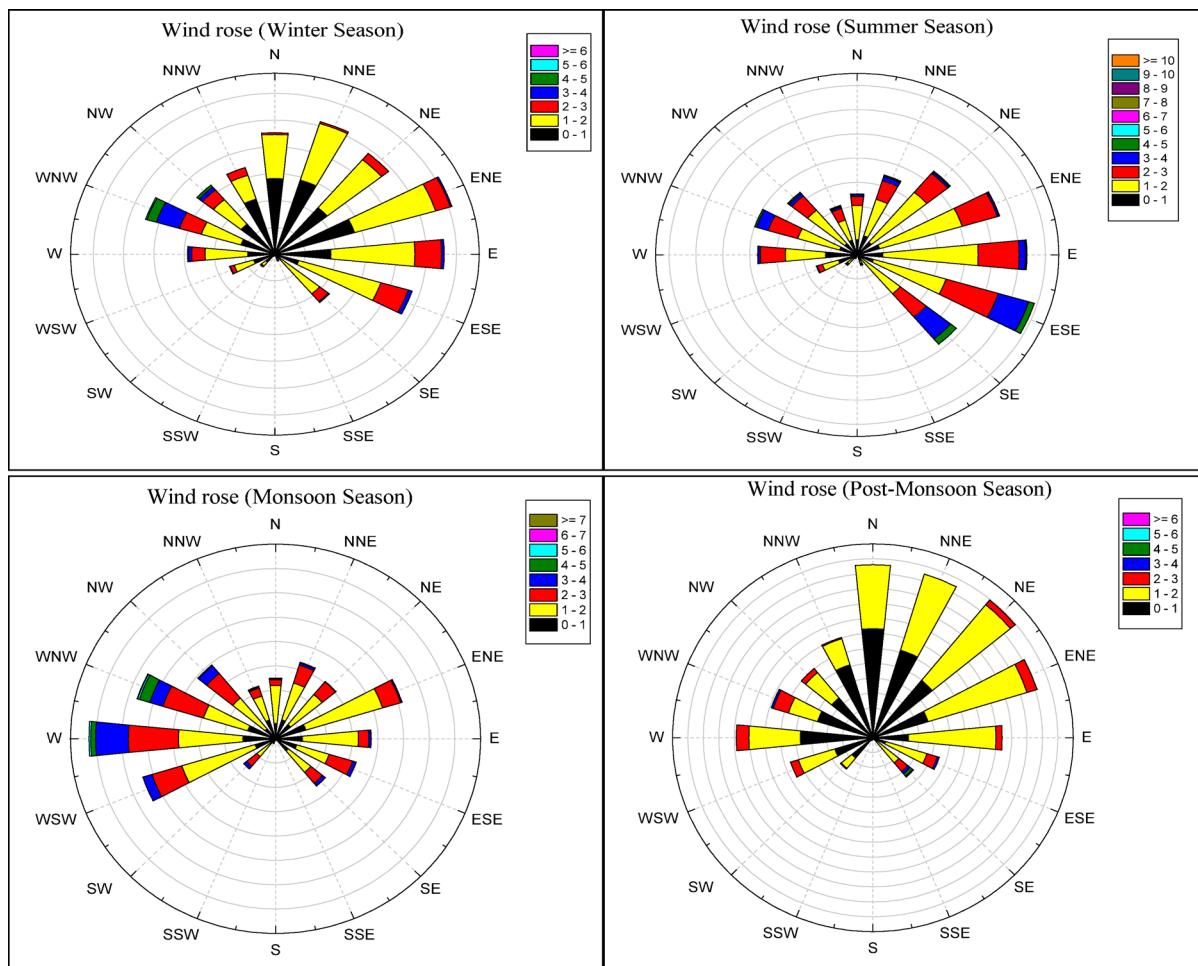


Fig. 4. Wind rose diagrams plotted during winter, summer, monsoon, and post-monsoon.

economic burden calculated for Agra by proportional scaling based on population size of India. Recent reports and research studies indicate an alarming trend about economic loss due to health risk attributed to air pollution and observed that it has surpassed previous estimates. These results demonstrate the problem's increasing severity and the pressing need for more proactive measures to lessen the detrimental effects of pollutants in the air on the general public's health and economy.

Discussion

The economic impact of air pollution-related health risks was investigated in this study from January to December 2022. This study was based on a certain district location. In comparison to WHO ($15 \mu\text{g m}^{-3}$ limit), USEPA ($50 \mu\text{g m}^{-3}$ limit), and NAAQS ($60 \mu\text{g m}^{-3}$ limit) standards, annual average concentrations of the site have consistently exceeded them in all seasons. The highest concentration of PM_{10} was found during the post-monsoon season (October–November). The winter and post-monsoon seasons have the highest PM concentrations close to urban roads because of inversions, or poor dispersion conditions⁷. The trend analysis shows a significant decreasing trend in PM_{10} during summer ($p=0.008$) and an increasing trend in post-monsoon ($p=0.039$). On Diwali night, the overall AQI was noticeably high at $461.5 \mu\text{g m}^{-3}$, and all pollutants, particularly PM_{10} and $\text{PM}_{2.5}$ pollutants^{61,62}. The backward trajectory plots across all months indicated consistent air mass transport patterns predominantly from the northeast and east directions. This suggests a recurring influence of regional and long-range transport on local atmospheric composition, emphasizing the need to consider seasonal wind patterns in air quality assessments. The critical health risk was found during the study period, except for the monsoon season, in Agra. AirQ + v.2.1.1 model helps to compute the attributable proportion of PM_{10} and the incidence rate per 100,000 people at risk per year. The study found that adults (age ≥ 30 years) are more affected by PM_{10} than children (age 1–5 years) or post-neonatal (age 1–12 months). The adult population over the age of 18 has the greatest annual death rate, with an average of 401 occurrences⁶³. The all-cause mortality is the primary health outcome evaluated in most of the previous studies⁶⁴. The average money to spend or invest to save one human life has been estimated to be INR 7,912 (US \$95.56). The economic cost was involved in human and government expenditure caused by air pollution to save human life. It is necessary to strike a balance between air quality and growth while lowering medical costs.

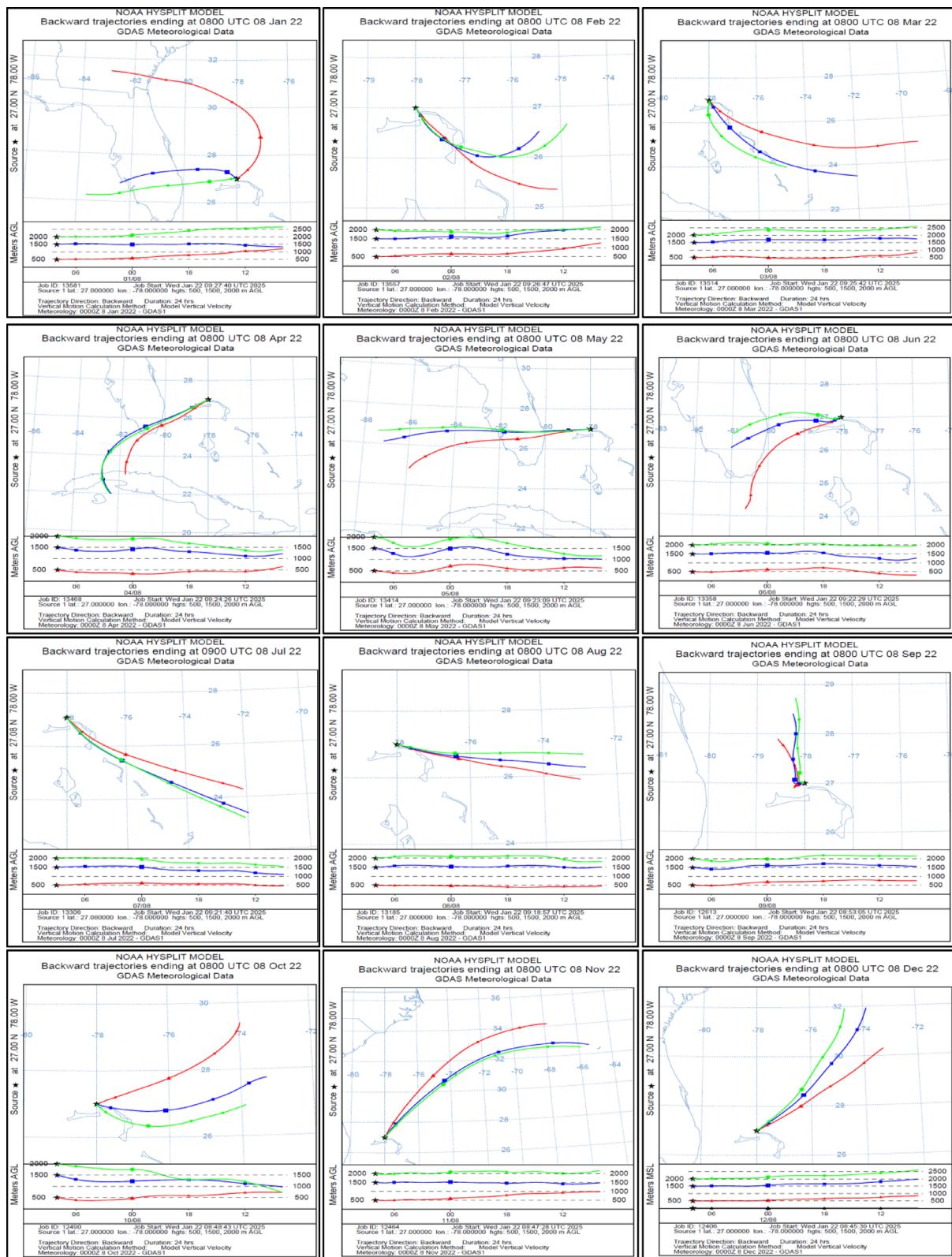


Fig. 5. Back-trajectory analysis during the 2nd week of every month in 2022.

The persistent elevation of PM_{10} levels in Agra underscores an urgent need for targeted air pollution control strategies. Key contributors—vehicular emissions, industrial activities, road dust, and construction—must be addressed through a multi-pronged policy approach. Firstly, vehicular emission control should be strengthened by enforcing Bharat Stage VI (BS-VI) fuel norms, expanding electric vehicle (EV) infrastructure, and phasing out

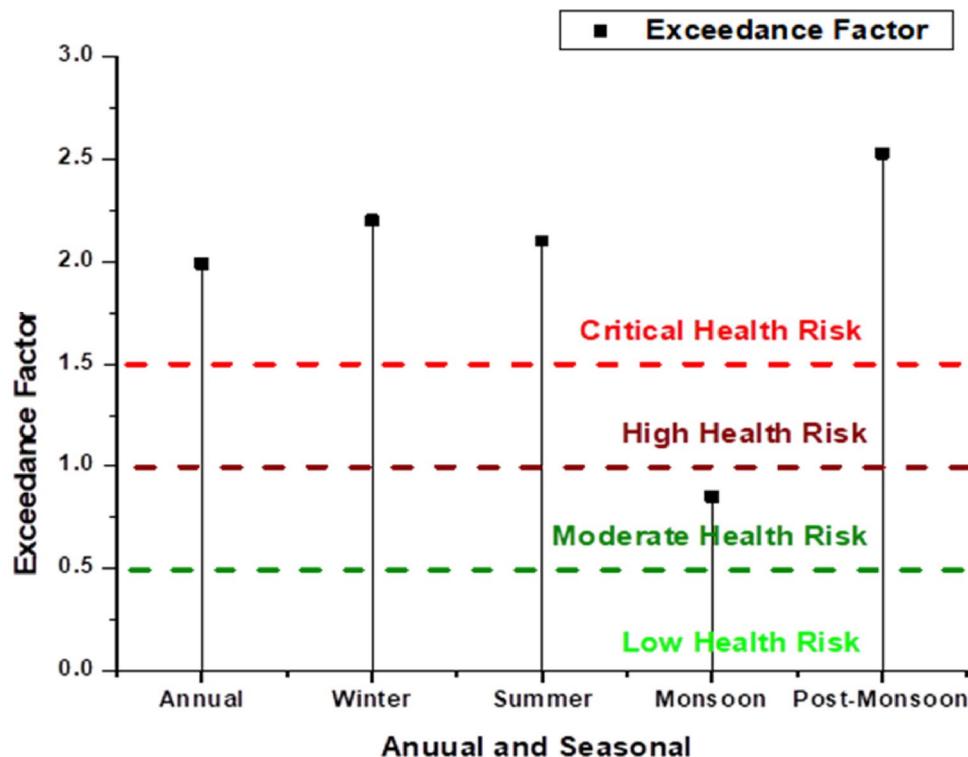


Fig. 6. Annual and Seasonal Exceedance Factors (EF) for PM_{10} Relative to NAAQS Standards.

Health risk	BIR	Relative risk	Cut off value	(a) EAP (%)	(b) ENCs	(c) (ENCs) per 100,000
Incidence of chronic bronchitis in adults (age ≥ 30)	7300	1.12 (1.04–1.19)	15	86.89 (51.3–95.8)	134456 (79335–148386)	6428 (3797–7091)
			50	80.7 (44.2–92.4)	6336 (3739–6993)	5969 (3267–6834)
			60	78.4 (41.9–90.9)	12311 (6581–14275)	5802 (3101–6727)
Post neonatal (age 1–12 months) infant mortality, all cause	3800	1.04 (1.02–1.07)	15	51.3 (30.5–71.1)	413745 (245679–573370)	1950 (1158–2702)
			50	44.2 (25.5–63.4)	355975 (205440–511117)	1678 (968–2409)
			60	41.9 (23.9–60.8)	337960 (193422–490450)	1593 (912–2311)
Prevalence of bronchitis in children (age 1–5 years)	4200	1.08 (1.0–1.19)	15	75.6 (0–95.9)	11878 (0–15058)	5597 (0–7096)
			50	68.1 (0–92.5)	10695 (0–14517)	5040 (0–6841)
			60	65.6 (0–91.0)	10295 (0–14291)	4851 (0–6735)
Mortality, all (natural) causes (adults age 30 + years)	1013	1.04 (1.03–1.06)	15	51.31 (41.9–65.7)	1102 (900–1412)	520 (424–665)
			50	44.2 (35.5–57.9)	949 (764–1245)	447 (360–587)
			60	41.9 (33.6–55.4)	901 (722–1190)	425 (340–561)
Mortality, IHD, adults age 30 +	3700	1.06 (1.01–1.10)	15	65.7 (16.7–82.6)	13796 (3506–17353)	6502 (1652–8178)
			50	57.9 (13.7–75.7)	12165 (2886–15906)	5733 (1360–7496)
			60	55.4 (12.9–73.3)	11634 (2704–15396)	5483 (1275–7255)
Mortality, respiratory, adults age 30 +	66	1.12 (1.06–1.19)	15	87.5 (65.7–95.9)	1224 (918–1342)	58 (43–63)
			50	81.4 (57.9–92.5)	1139 (809–1294)	54 (38–61)
			60	79.2 (55.4–91.0)	1107 (774–1274)	52 (36–60)
Mortality due to lung cancer for adults	45	1.08 (1.04–1.13)	15	75.6 (51.3–89.4)	721 (489–853)	34 (23–40)
			50	68.1 (44.2–83.7)	649 (421–798)	31 (20–38)
			60	65.6 (41.9–81.6)	625 (399–778)	29 (19–37)

Table 3. (a) estimated attributable proportion % (EAP), (b) estimated number of attributable cases (ENCs) and (c) estimated number of attributable cases (ENCs) per 100,000 populations at risk due to long run exposure to PM_{10} ($\mu\text{g}/\text{m}^3$) with confidence intervals (CI 95%) for relative risk.

Area	Year	Premature deaths/heath risk	Tool*	Economic loss	References
India	2022	5 million	VSL	US\$ 135 billion	Present study
India	2022	-	-	US\$ 150 billion	53
China (28 cities)	2020	3 million	VSL	US\$ 637 billion	56
Global	2019	6.4 million	-	US\$ 8100 billion	57
India	2021	1.7 million	-	US\$ 95 billion	58
India (31 cities)	2021	0.08 million	VSL	US\$ 92 billion	61
India	2019	1.67 million	DALYs	US\$ 29 billion	59
USA	2021	0.12 million	-	US\$ 820 billion	60
Guangxi, China	2019	-	VSL	US\$ 5 billion	61
Indonesia (5 districts)	2019	-	-	US\$ 437 billion	26
Agra, India	2014	-	VSL, CoI	US\$ 254.5 million	6
Agra, India	2022	-	VSL	US\$ 202.58 million	Present study

Table 4. Comparison of the monetary expenses and health risks related to air pollution in different places.

*VSL (Value of Statistical Life); CoI (Cost of Illness); DALYs (Disability-Adjusted Life Year).

vehicles older than 15 years, particularly diesel-powered ones. Secondly, industrial emissions, especially from brick kilns and small-scale units, must be regulated through the adoption of cleaner technologies and relocation of high-emission units away from residential zones. Thirdly, road dust can be minimized by regular mechanized sweeping and paving of unsealed roads. Public awareness campaigns should also be launched to educate citizens about pollution sources, mitigation practices, health risks, and monetary burden. Crucially, these interventions must be aligned with public health priorities. Elevated PM_{10} levels are linked to respiratory and cardiovascular diseases, with vulnerable populations—such as children, the elderly, and those with pre-existing conditions—at heightened risk. Therefore, integrating air quality management into urban health planning, establishing early warning systems for pollution episodes, and improving access to healthcare services in affected areas are essential steps. A coordinated effort among local government bodies, regulatory agencies, and the public will be vital to safeguarding Agra's environmental and public health future. Quantifying health-related economic losses aids policymakers, healthcare workers, and researchers.

In this study health risk assessment incorporated 95% confidence intervals for relative risk estimates (as shown in Table 3), which reflect statistical uncertainty in the exposure-response functions. These intervals were based on established epidemiological studies that quantify the health risks associated with long-term PM_{10} exposure. While we did not perform a full-scale sensitivity analysis, we ensured the robustness of our estimates using high-quality, site-specific primary data. PM_{10} concentrations were measured using calibrated Envirotech respirable dust samplers, equipped with Whatman GF/A filters and operated at a constant low-volume flow rate of 16.67 L/min. The flow rate was verified hourly using a calibrated rotameter to minimize instrumental error. Furthermore, field blanks were used to account for background contamination, and sampling was consistently performed over a 24-hour period to capture diurnal variations.

This study has certain limitations. Firstly, this study was focused on Agra city due to the specific research objectives and availability of reliable data for the region. PM_{10} data were collected from a single representative monitoring location at Agra city. Secondly, the direct costs were not included in this work, such as hospital admission, outpatient visits, medication, labour productivity, and agricultural yield. The national economic loss figure was extrapolated from Agra's estimated burden by proportional scaling based on population. In the present study, groups such as post-neonatal (1-12 months), children (age 1-5 years), and adults (age ≥ 30 years) were not assessed separately in economic valuation due to the unavailability of age-specific data for the study area. Future studies may incorporate age-stratified exposure and valuation approaches to better capture the risks to vulnerable populations. The assumptions were applied in each model, such as default relative risks and baseline incidence rates are assumed to remain constant over the exposure period in AirQ+, treated each prevented mortality equally in economic terms in VSL calculations, and meteorological data used from the Global Data Assimilation System (GDAS) are assumed to be representative and reliable for the back-trajectory analysis.

To summarize, comprehending the financial impact of health hazards resulting from air pollution is crucial for well-informed decision-making, focused interventions, and cooperative endeavours to establish a more salubrious milieu for all. Cleaner air leads to fewer air pollution-related illnesses, reducing the money spent on medical treatments and improving economic welfare and growth rates⁶⁵. Governments should take effective measures to prevent risks to public health and improve the quality of pollution treatment to maintain a healthy and sustainable economic system⁶⁶. Highlight the significant negative effects of urbanization on the environment since rising surface temperatures alter local climates and harm ecological health, air quality, and overall thermal comfort⁶⁷. With outdoor air pollution responsible for 61% of pollution-related deaths globally, it is the single biggest contributor to pollution-related deaths⁶⁸. In India, where resources are scarce compared to various development goals, it is especially crucial to carefully set priorities and policies for controlling air pollution based on the health effects and expected benefits. The policy constraint requires a nation's national air quality standards to be reviewed, considering increased pollutant background concentrations^{69,70}. Promoting public participation is the education and mobilization of citizens to become aware and push the government to aggressively adopt or implement mitigation measures⁷¹. Future shortages of essential services and a decline

in agricultural lands are caused by population growth and the expansion of built-up areas. Spatial planning is desperately needed for both the sustainability of urban growth and the high standard of living for citizens⁷². The findings indicate that corporate environmental responsibility consensus (CCER) and the level of government environmental enforcement are significantly positively correlated, but that CCER has a negative impact on the frequency of environmental emergencies⁷³.

A country may accomplish sustainable economic development by giving priority to initiatives to reduce air pollution through a circular economy model. The three primary pillars of the circular economy are resources and good reuse, waste and pollution reduction, as well as the restoration and recycling of organic systems. A circular economy advances at least 12 out of the 17 SDG objectives⁷⁴. Circular strategies have the potential to reduce global greenhouse gas emissions by 39% and the use of non-circular resources by 28%, according to the Circularity Gap Report⁷⁵. India can benefit annually from circular economy principles to the tune of US\$ 218 billion (INR 14 lakh crore) in 2030 and US\$ 624 billion (INR 40 lakh crore) roughly in 2050, which is equivalent to 30% of the country's current GDP.

Methods

Characteristics of the site

The study was conducted in the Indian city of Agra, which is in Uttar Pradesh's northern region, well known for the Taj Mahal, which occupies a key part in India's touristic landscape and is a symbol of the country's culture and history. Agra is well known for its beautifully patterned carpets, leather shoes, and marble inlay work. Situated on the Yamuna River's banks, it is recognized as a World Heritage Site can be considered as a representative site as it is one of the highly polluted cities in our country at the same time is situated over the Indo-Gangetic basin, which hosts 40% of Indian population and 60% of Indian territory area. It is situated at N 27° 10' 59.988" and E 78° 1' 0.012", covering an area of 121 square kilometres (km²). On a list of cities having the worst air quality, Agra comes up at number four⁷⁶.

The Dayalbagh region, a suburban location 10 kilometres from Agra's industrial district, was chosen for ground monitoring showed in Fig. 7 Dayalbagh is predominated by vegetation due to agricultural activities. Sampling was done at the Technical College of Dayalbagh Educational Institute in Dayalbagh (27° 13' 46.0056" N and 78° 0' 25.8444" E with size approximately 8.97 km²), Agra, India. The sampling site is located along the side of a road that sees mixed vehicular traffic on the order of 1000 cars per day, and a National Highway (NH-II) crosses the road 2 km south, with dense vehicular activity. The area recorded high summer temperatures often exceeding 40 °C, while winter temperatures dropped as low as 5 °C. Relative humidity varied significantly, ranging from 20 to 90%, with peak levels during the monsoon months (July–September). Wind patterns were predominantly northwesterly in summer and shifted to easterly during the monsoon, influencing pollutant dispersion. The average annual rainfall was around 650 mm, mainly concentrated in the monsoon season.

Mass concentrations of PM₁₀

To quantify reliably and evaluate particulate matter having a size of 10 micrometres or less, samples of respirable suspended particulate matter in the atmosphere at the site have been collected by using Envirotech Respirable Dust Samplers with Whatman glass microfiber grade GF/A, 47 mm diam. Filters. The blower motor assembly, filter holder, volumetric flow controller, timer, and anodized aluminium cover are all included in the air sampler. It draws precise quantities of air through a known-weight filter paper. It's a high- volume sampler that keeps a constant flow rate (16.67 L min⁻¹) during the sampling process at a flow rate of 10 L min⁻¹. The filter attached to the sampler collects the suspended particulate debris, which is used for laboratory analysis. In the sampler's filter holder, a pre-desiccated, pre-weighed, and sterilized filter is managed, and sampling was carried out for 24 h (10:00 AM to 10:00 AM), 1–2 times per week, from January to December 2022. A total of 74 observations were recorded, with approximately 17–20 sampling events conducted per season (as shown in Table 1). Gravimetric analysis was used to determine the mass concentrations of PM₁₀ in the ambient air. PM₁₀ concentration was calculated by dividing the filter mass difference by the total air volume sampled to determine the mass concentration. Where W_f is final weight, W_i is initial weight, and AvgFlowRate (average flow rate).

$$\text{Concentrations of PM}_{10} = \frac{W_f - W_i * 10^6}{\text{AvgFlowRate} * 24 * 60}$$

Statistical analysis of concentrations of PM₁₀

The Mann-Kendall test and Sen's slope estimator are used to analyze trends in time series data, like PM₁₀ concentration levels, and determine if there's a statistically significant monotonic trend (upward or downward). The Mann-Kendall test detects the presence of a trend, while Sen's slope estimator provides an estimate of the magnitude of that trend. The significance level selected for the Mann-Kendall test was set at a 95% confidence level, indicating that if $p < \alpha$ ($\alpha = 0.05$), it indicates a significant trend. While MK is traditionally used for long-term trend detection, recent environmental studies have applied MK and Sen's slope tests on seasonal or short-term datasets to explore intra-annual trends⁷⁷. A statistical measure associated with the Mann-Kendall test on 75 observations over the study period January to December 2022. Higher values indicate stronger trends, typically positive if > 1.96 . Additionally, Sen's slope is used to find the direction (positive or negative) and magnitude of the trend, providing insights into whether the variable was increasing, decreasing, or remaining stable over time^{78–80}.

The HYSPLIT is used to generate back-trajectory plots, developed by the National Oceanic and Atmospheric Administration (NOAA). It helps in identifying the origin and movement of air masses arriving at the study area. This model traces the path of air masses arriving at the Agra region (27.00°N, 78.00°W) above ground



Fig. 7. Location of sampling site, technical college, DEI, Dayalbagh, Agra.

level (AGL) with backward direction at 0800 UTC in the past 24 h during the 2nd week of every month in 2022. By tracking the routes of air parcels backward in time from a certain area, it assists in locating the causes of air pollution. It helps identify potential pollutant source regions and assess the transboundary or regional nature of air pollution^{81,82}.

Health risk assessment (HRA)

Health risk assessment entails identifying, categorizing, and quantifying the health hazards concerned with exposure to airborne contaminants. It considers several variables, including pollutant concentrations, exposure times, and population vulnerability. Exceedance factor, which is a useful tool for identifying the deteriorating air quality brought on by higher pollution levels. It's determined by dividing the pollutant's yearly mean concentration by the applicable threshold set by the National Ambient Air Quality Standards (NAAQS). It is frequently used for managing and monitoring air quality. It shows how far the pollutant concentration detected is over the specified limit. Air quality-related health risks can be divided into four categories: moderate (EF from 0.5 to 1.0), low (EF is less than 0.5), high (EF from 1.0 to 1.5), and critical (EF is more than 1.5). Exceedance factor is measured by the following formula.

$$\text{Exceedance Factor} = \frac{\text{Yearly observed concentration of criterion pollutant}}{\text{Annual standard for particulate matter}}$$

Population Weighted Mean (PWM) is helpful in understanding the risk of contaminants to the local population in the selected area. In other words, it is a statistical metric used to determine the average value of a particular variable that considers the distribution of people across various places. There i is stand for each computation unit in the domain, P_i is the population at a specific cell location, C_i is the concentration of particles at that same cell location, and P_{tot} is the total population in the domain of interest.

$$\text{PWM} = \sum_{i=1}^n \frac{P_i * C_i}{P_{tot}}$$

Population Attributable Fraction (PAF) is used to determine the proportion of the disease burden within a community that can be attributed to a particular risk factor. It helps to categorise and quantify the effects of exposure to air pollution (PM_{10}) in terms of public health by using the AirQ+ v.2.1.1 model developed by the WHO^{5,6,83}. The excess attributable proportion % (EAP), the excess number of attributable cases (ENCs), and the excess number of attributable cases (ENCs) per 100,000 populations at risk due to long run exposure to PM_{10} (mg m^{-3}) with confidence intervals (CI 95%) for relative risk. This study examines morbidity (the prevalence of bronchitis in children aged 1–5 years, the incidence of chronic bronchitis in adults aged ≥ 30), and mortality (the mortality from ischemic heart disease, respiratory, all (natural) causes, lung cancer in adults aged ≥ 30 , and infant mortality (all cause) in post-neonatal (age 1–12 months). This model relies on methodologies and concentration-response functions derived from epidemiological studies. PAF was calculated based on mean average concentration of PM_{10} , geospatial data, cutoff value ($15 \mu\text{g m}^{-3}$ (WHO limit), $50 \mu\text{g m}^{-3}$ (USEPA limit), $60 \mu\text{g m}^{-3}$ (NAAQS limit)), values of relative risks (defaulted in AirQ+), population of study area, and incidence rate (the number of new cases of a disease per population in a given time). It takes into account the possibility of death, the contributing causes of particulate matter, and the effects of on-going exposure on people's health⁸⁴. According to the report, 18% of deaths are attributable to air pollution⁸⁵.

Value of a statistical life (VSL)

It is used to determine how much money society would be willing to spend to avoid a statistical fatality^{6,86–88}. The concept of “statistical life” describes the idea that the VSL is more about the statistical value connected with reducing an individual's overall risk of mortality than it is about valuing the life of a particular individual. This method attempts to estimate the present value of future benefits (usually income or willingness to pay) over the remaining life years, it's a type of human capital approach and based on discounted life income. Developing a fictitious market for the risk of death under discussion and determined using VSL is a basic technique for calculating the monetary cost of an advantageous economic effect, such as a reduction in the risk of death⁸⁹. As per the review of the literature, a number of studies have been done based on the VSL method during the last decades^{90–97}. It is best to estimate the cost society is willing to pay to lower the probability of death in order to determine the values of a statistical life⁹⁸. After an EPA review, 26 studies were found to reflect valid and reasonable methods⁹⁹. Since there is no way to determine the market value of a human life, the financial burden of air pollution-related health risks and the monetary evaluation of those risks' effects on health are calculated using the loss of income due to death¹⁰⁰. VSL is calculated using the following formula.

$$\text{VSL} = \sum_{i=0}^x \frac{y}{e / (1 + d) / \mu}$$

Where y is the yearly average income, e is life expectancy, μ is the average age of the population, and d is the rate of discount¹⁰¹ and x is the gap between the population's average age and life expectancy.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

“D.K. Wrote the main manuscript and R.K. and S.P.S. reviewed the manuscript.”

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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