



# Assessment of benzene and toluene emissions in National Capital Region (NCR): Implications for health risks and ozone formation

Nancy Kaushik<sup>1,2</sup> · A. K. Mishra<sup>3</sup> · Rupesh M. Das<sup>1,2</sup>

Received: 6 June 2024 / Accepted: 21 July 2024  
© The Author(s), under exclusive licence to Springer Nature B.V. 2024

## Abstract

This study investigates benzene and toluene concentrations in Delhi and National Capital Region (NCR), India, assessing health risks and impacts on air quality, focusing on their role in ozone formation. Data from 56 monitoring stations identified 18 locations where benzene levels exceed the national safe limit, primarily due to traffic emissions and seasonal variations. Benzene concentrations peaked at  $15.06 \mu\text{g}/\text{m}^3$  in Loni, Ghaziabad, during winter. Seasonal analysis indicated higher benzene levels during winter and post-monsoon periods due to lower planetary boundary layer heights (PBLHs) trapping pollutants near the ground. Health risk assessments revealed probable cancer risks for residents, with children facing higher risks than adults. Using the Ozone Formation Potential (OFP) metric and Maximum Incremental Reactivity (MIR) coefficients of 0.72 for benzene and 4.0 for toluene, the study predicted OFP values for various hotspots. Toluene's significant contribution to ozone formation was evident, with the highest concentration observed at Charkhi Dadri, Haryana ( $29.65 \pm 2.26 \mu\text{g}/\text{m}^3$ ), surpassing the WHO's air quality guidelines of  $120 \mu\text{g}/\text{m}^3$ , and the highest benzene concentration at Loni ( $7.3 \pm 0.8 \mu\text{g}/\text{m}^3$ ). Toluene/benzene ratio and principal component analysis identified automobiles and industrial activities as significant pollution sources. The study underscores the urgent need for stricter emission controls, cleaner fuels, and improved urban planning to reduce these pollutant's negative impacts on the environment. Elevated VOC levels and associated health risks necessitate immediate action to protect public health and improve air quality in Delhi NCR. These results emphasize critical need for interventions to address benzene and toluene pollution comprehensively.

**Keywords** Benzene · Toluene · Carcinogenic and non-carcinogenic risks · Delhi-NCR · Ambient air

## Abbreviations

VOCs	Volatile Organic Compounds	GGN	Gurugram
BTEX	Benzene, Toluene, Ethylbenzene, Xylene	FBD	Faridabad
HQ	Hazard Quotient	GZB	Ghaziabad
LTCR	Lifetime Cancer Risk	NO <sub>2</sub>	Nitrogen dioxide
RfD	Reference Dose	NO	Nitrogen oxide
NCR	National Capital Region	O <sub>3</sub>	Ozone
NAAQS	National Ambient Air Quality Standards	O <sub>2</sub>	Oxygen
CPCB	Central Pollution Control Board	BS	Bharat Stage emission norms
UP	Uttar Pradesh	USEPA	United States Environmental Protection Agency
HRY	Haryana	PBLH	Planetary Boundary Layer Height
		MIR	Maximum Incremental Reactivity
		OFP	Ozone Formation Potential
		DJF	December January February
		MAM	March April May
		JJA	June July August
		SON	September October November
		T/B	Toluene to benzene ratio
		PCA	Principal Component Analysis
		WHO	World Health Organisation

✉ Rupesh M. Das  
rupesh@nplindia.org

<sup>1</sup> Academy of Scientific and Innovative Research, Ghaziabad, India

<sup>2</sup> CSIR- National Physical Laboratory, Dr. K.S. Krishnan Road, New Delhi 110012, India

<sup>3</sup> Bihar Mausam Sewa Kendra, Patna, India

## Introduction

Benzene and toluene are volatile organic compounds (VOCs) that significantly threaten human health and the environment. These compounds, part of the BTEX group (benzene, toluene, ethylbenzene, and xylene), contribute to poor air quality and adverse health outcomes. They play an important role in the formation of ground-level ozone, a secondary pollutant that poses risks to respiratory health, particularly in the summer when high temperatures increase ozone levels (Petrus et al. 2024; Zawacki et al. 2018). Additionally, they contribute to the formation of secondary organic aerosols (Henze et al., 2008), affecting climate (Zhu et al. 2022). Major human factors include vehicular emissions, petroleum refineries gasoline evaporation, fuel combustion, solvent use, and gas system leaks. Tobacco smoke and solid waste breakdown also emit these VOCs (Caselli et al. 2010). Benzene and toluene are hazardous air pollutants as classified by US Clean Air Act of 1990, in terms of its carcinogenicity and mutagenicity. Among them, benzene is considered the most toxic, earning a Group 1 human carcinogen classification by the International Agency for Research on Cancer and a Class A human carcinogen designation by the US Environmental Protection Agency. Long-term exposure to benzene can cause serious health problems, including various types of leukaemia, anaemia, genetic mutations, blood disorders, multiple cancers, reproductive issues, and damage to the kidneys, liver, and central nervous system. Short-term exposure to benzene and toluene can result in eye, nose, and throat irritation, fatigue, respiratory difficulties, lung damage, dizziness, memory loss, and a range of respiratory symptoms. Chronic exposure may also have detrimental effects on maternal health and infant development (Kim et al. 2009; IARC 2002; USEPA 1997, 1998). To compute the harmful impacts researchers often compute, Hazard Quotient (HQ), and Lifetime Cancer Risk (LTCR). HQ is used to gauge non-cancerous health effects from a particular substance by comparing the exposure level to a Reference Dose (RfD), which is the maximum daily amount of a substance that can be taken over a lifetime without significant risk. Expressed as a probability, it reflects the chance of developing cancer over a lifetime due to exposure, considering factors like substance potency, exposure duration, and route. In India, the levels of anthropogenic VOCs in the atmosphere have become a significant concern, particularly in urban areas with heavy traffic and industrial activities. Studies show that the amount of VOCs often exceeds the safe limits, contributing to air pollution and posing health risks to the population (Rizwan et al. 2013). Additionally, studies have shown that post-harvest burning of agricultural residue of paddy fields leads to significant

contribution to ambient levels of benzenoids in the North-west Indo Gangetic Plains of India (Chandra & Sinha 2016). In Delhi NCR, where air pollution is a pressing issue, volatile organic compounds (VOCs) such as benzene and toluene pose significant challenges. The rapid pace of urbanization and industrial expansion has only served to amplify the emission of these deleterious substances, predominantly stemming from vehicular exhaust, industrial processes, and combustion activities (Kermani et al. 2021; Mehta et al. 2020). The impact of BTEX in the context of atmospheric chemistry and public health is significant; yet, within the Indian regulatory guidelines, only benzene is subject to an annual threshold limit as per the National Ambient Air Quality Standards (NAAQS). Apart from benzene, there are no established protocols for the quantification of ambient VOC levels. However, the Central Pollution Control Board (CPCB) is progressing in this field and has set an annual limit of  $5 \mu\text{g}/\text{m}^3$  for benzene (CPCB 2009). While, BTEX pollutants are recognized for their health hazards, research into their precise concentrations and impacts in India is insufficient, primarily due to the focus on larger cities (Ramírez et al. 2012). In India, previous studies on air pollution have mostly focused on parts of Delhi (Garg et al. 2018; Singh et al. 2016, Kumar et al. 2014) neglecting the entire NCR region, a key factor in the area's overall pollution. Delhi, a landlocked city surrounded by high-rise buildings of Gurugram, Noida, and other parts of NCR, traps pollutants, leading to severe pollution events. The poor ventilation coefficient during winter exacerbates the city's air quality issues, indicating a high pollution potential (Saha et al. 2019; Iyer and Raj 2013). This research addresses this gap by covering the entire Delhi NCR region, known for its high pollution levels, and aims to improve air quality management strategies like the Graded Response Action Plan, crucial during winter and post-monsoon seasons. The study measures benzene and toluene levels, identifies their sources, examines their roles in ozone formation, and assesses both cancerous and non-cancerous health risks for residents and commuters in the region.

## Methodology

### Site selection and analysis

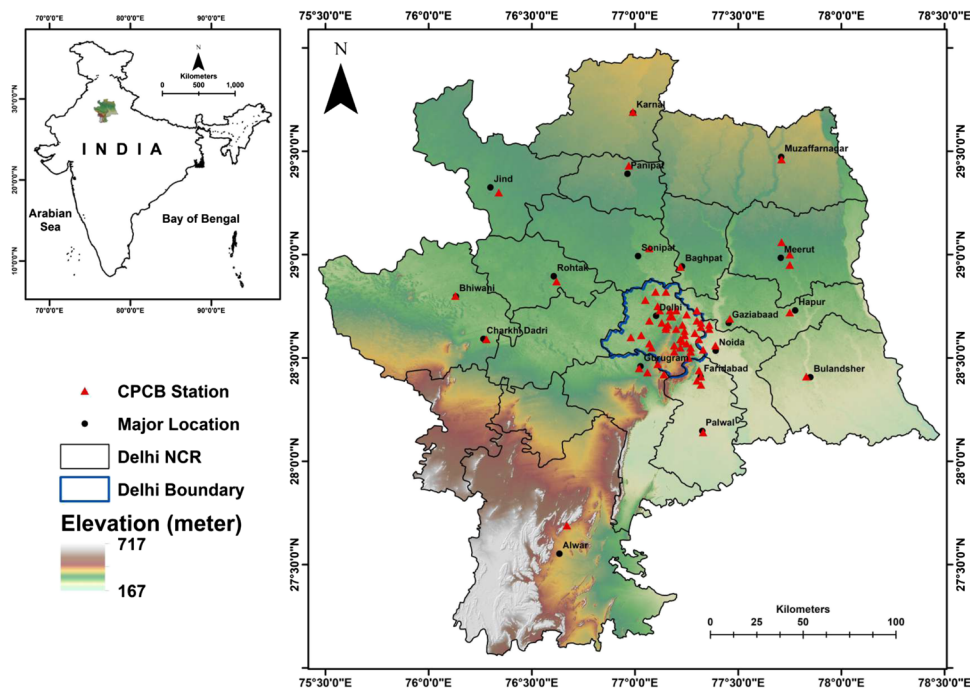
The study area consists of entire Delhi and National Capital Region (NCR) of India, spanning from coordinates  $28.4020^\circ \text{N}$ ,  $76.8260^\circ \text{E}$ , which includes 62.52% of urban, and 37.48% of rural sections of Haryana, Uttar Pradesh, and Rajasthan. Regions under Haryana and Uttar Pradesh are fast growing areas of the NCR and are about 275 m above the mean sea level, surround Delhi on three sides. The NCR region is a

part of the Indo-Gangetic Plain (IGP), and has an area of 55,083 km<sup>2</sup> and a population of 46 million with density of population as 1,105 persons per square kilometre which is too high compared to the national levels (National Capital Region Planning Board 2016). The study analysed data from 56 continuous monitoring stations across the National Capital Region of Delhi. After refining the dataset by excluding zero values, outliers, and duplicates, the analysis focused on 10 stations in Haryana, 7 in Uttar Pradesh, 2 in Rajasthan, and 26 in Delhi. Details of these stations along with demography details of NCR is shown in Fig. 1 and Table 1. The area's dynamic weather patterns, characterized by mild winters (December–February; 5–10 °C), semi-arid climate with hot summers (March–May; 40–48 °C), monsoon season (June–August) with heavy rainfall, and the post-monsoon season (September–November) (Praveen et al. 2020). The

winds change direction seasonally, blowing from the southwest in summer and from the northwest in winter (Shukla et al. 2020). These unique weather patterns, combined with strategic geographical features, provide an excellent opportunity to study less-known cancer-causing chemicals in the air and their impacts. The region is a hub for commerce, transportation, industry, and some agriculture, with significant pollution coming from vehicles, factories, services, and construction. On regular workdays, many vehicles commute between the NCR and Delhi, influencing the area's dynamics.

This study investigates hourly data for two-years, from January 2022 to January 2024, encompassing continuous data for 24 months (730 days) with 24 readings per day per CAAQMS station, for VOCs (benzene and toluene), as well as NO<sub>2</sub>, NO, and O<sub>3</sub>. The data collection has adhered

**Fig. 1** Study area map showing Delhi NCR CPCB continuous air quality monitoring stations



**Table 1** Continuous Air Quality Monitoring Stations across Delhi NCR

Delhi NCR Location	Area (Km <sup>2</sup> )	Population (in thousands)	Sites with CAAQMS
Haryana	25,327	11,031	Bhiwani, Sonipat, Charkhi Dadri, Faridabad, Gurugram, Jind, Karnal, Palwal, Rohtak, Panipat
Uttar Pradesh (UP)	14,826	14,576	Noida, Ghaziabad, Anand vihar (Hapur), Meerut, Muzaffarnagar, Bulandshah, Baghpat
Rajasthan	13,447	3,674	Alwar, Bharatpur
Delhi	1,483	16,788	Rohini, Anand Vihar, Sirifort, Chandni chowk, Dwarka Sector 8, IBHAS Dilshad Garden, Shadipur, JNU stadium, Pusa, KS shooting range, Major DC std, Sri Aurbindo Marg, Mandir Marg, Najafgarh, Narela, NSIT Dwarka, Okhla, Patparganj, Ashok Vihar, Punjabi Bagh, RK Puram, Sonia Vihar, Vivek Vihar, Wazirpur, Mundka, Nehru Nagar

to the guidelines of the Central Pollution Control Board (CPCB) and the U.S. Environmental Protection Agency (EPA). A variety of measurement techniques were utilized, including gas chromatography with a photoionization detector (GC-PID) for VOCs, chemiluminescence for NO<sub>2</sub> and NO, and ultraviolet (UV) photometry for O<sub>3</sub>. Meteorological information was obtained from the CPCB's database, and the planetary boundary layer height (PBLH) data was acquired from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) with a resolution of 0.5 × 0.625° for the years 2022 and 2023. The objective was to identify variations in the benzene and toluene concentrations during rush hours, defined as 9:00 AM to 11:00 AM, and the low traffic hours, from 2:00 PM to 4:00 PM, to understand the impact of vehicular flow on pollutant levels.

### Assessment of health risks

To evaluate the health risk assessments, LTCR and HQ have been computed according to USEPA methodology and Zhang et al. (2015). The LTCR calculation begins with determining the daily exposure (E) in mg/kg/day using the Eq. (1):

$$E = (C \times IRa \times DA) / BW \quad (1)$$

where,

C = benzene concentration in ambient air (mg/m<sup>3</sup>),  
IRa = respiratory rate (0.83 m<sup>3</sup> h<sup>-1</sup> for adults, 0.87 m<sup>3</sup> h<sup>-1</sup> for children; Zhang et al. 2015).

DA = duration of exposure (8 h/day) (Indian working hours; as per Ministry of Labour & Employment, Government of India 2023).

BW = body weight (65 kg for adults, 36 kg for children as per USEPA, 2009).

The calculated value of daily exposure (E) has been employed in the Eq. (2), to estimate

the LTCR,

$$LTCR = E \times SF \quad (2)$$

where, SF = Slope Factor (2.9 × 10<sup>-2</sup> mg/kg/day<sup>-1</sup>), as classified by the EPA Cancer classification and stated in the Risk Assessment Information System.

Similarly, the hazard quotient (HQ) has also been estimated through Eq. (3)

$$HQ = CY / RfD \quad (3)$$

where,

CY = average daily concentration,

RfD = BTEX inhalation reference dose i.e., 0.003, 5, 1, and 0.1 mg/m<sup>3</sup>, respectively according to ATSDR 2005.

### Potential for ozone formation

The ozone formation potential (OFP) has been computed using Carter's 1994 methodology which considers the maximum incremental reactivity (MIR) to measure this reactivity. The MIR indicates the amount of ozone (in grams) produced for each gram of VOC that initiates the VOC-NO<sub>x</sub> reaction. It measures a compound's contribution to ozone production in the atmosphere (Carter 1990, 1994, 2010; Hoque et al. 2008). The MIR value for toluene is 4.02, and for benzene, it is 0.79. The OFP calculation involves multiplying the VOC concentration by its MIR value (Tiwari et al. 2010).

## Results and discussion

### Hotspot areas

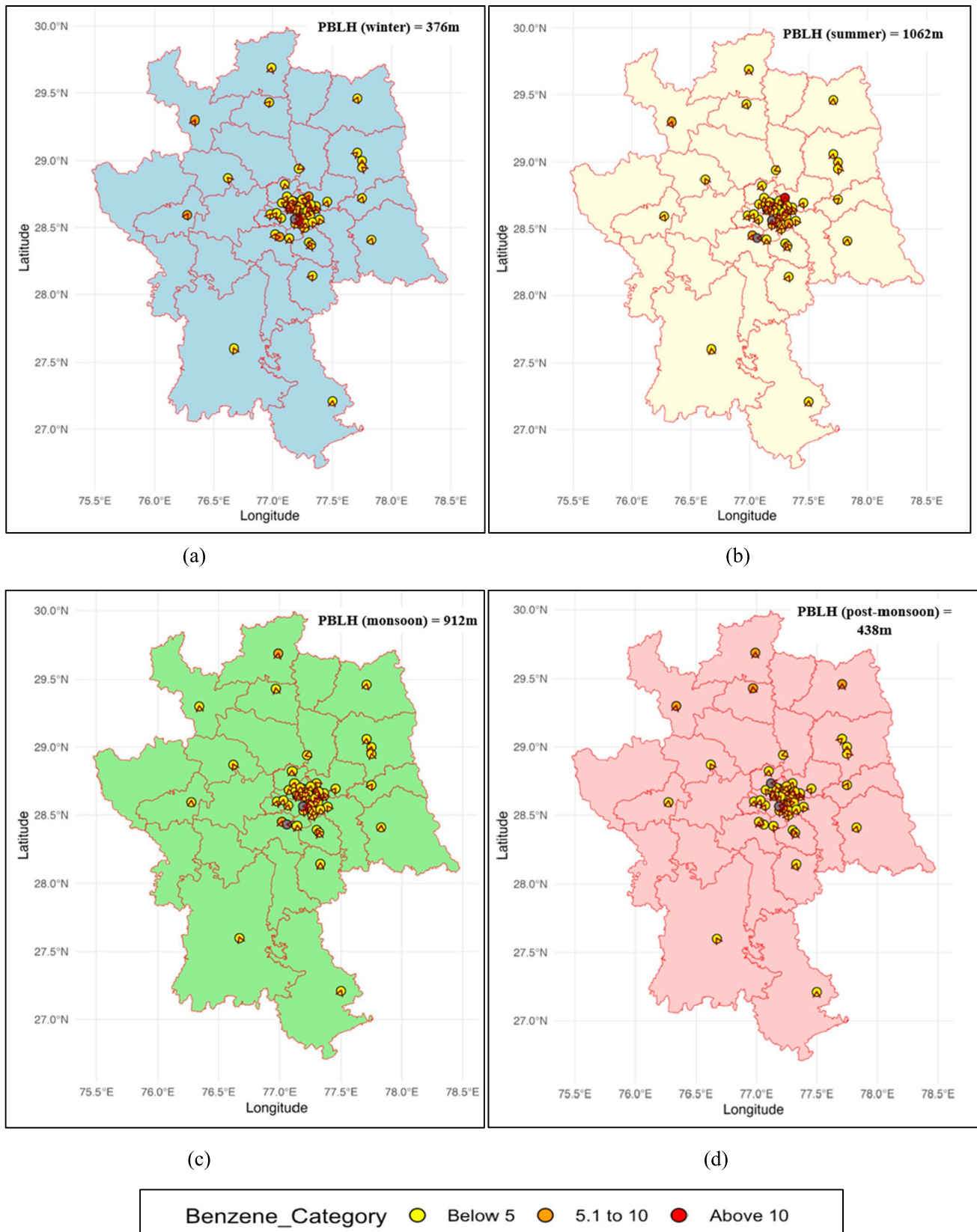
The analysis of data from 56 monitoring stations across Delhi NCR revealed that 18 locations are hotspots for benzene, a known carcinogen, with levels surpassing the NAAQ standard of 5 µg/m<sup>3</sup> annually. The monthly hotspot data is catalogued in Table 2, with consistent hotspots including Anand Vihar, Chandni Chowk, Shadipur, Siri fort, NSIT Dwarka, and Okhla from Delhi; Charkhi Dadri, Gwal Pahadi, Jind, Karnal, Palwal, Panipat, Sector 11 Faridabad, Sector 51 Gurgaon, Vikas Sadan Gurgaon from Haryana; and Loni, Muzaffarnagar, and Sector 125 Noida from Uttar Pradesh. These findings highlight the urgent need for interventions to control benzene pollution and safeguard public health in these areas. Similar to the European Commission's progressive measures, which set a benzene limit of 5 µg/m<sup>3</sup> in 2000, reduced it to below 1 µg/m<sup>3</sup> in 2006, and successfully achieved undetectable levels of benzene in the air by 2010. Similarly, in the context of NCR, these strategies should prioritize reducing benzene exposure through enhanced monitoring, rigorous regulatory measures, and widespread community awareness initiatives.

### Effect of meteorology on levels of benzene

Figure 2 illustrates the seasonal changes in the planetary boundary layer (PBL) and wind patterns that influence benzene levels across various locations in Delhi NCR. Benzene concentrations peak at an average of 15.06 µg/m<sup>3</sup> in the Loni area of Ghaziabad, Uttar Pradesh. During the winter (PBL height: 376 m) and post-monsoon (PBL height: 438 m) seasons, the maps show a higher prevalence of orange and red dots, indicating benzene concentrations above 5 and 10 µg/m<sup>3</sup>. The lower PBL height and colder air during these seasons trap benzene at ground level due to inversion, preventing its dispersion (Hosseinpour et al. 2024). In contrast, the summer and monsoon seasons exhibit fewer or no red dots

**Table 2** Monthly hotspot areas of benzene (> 5 µg/m<sup>3</sup>)

JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Sirifort, Delhi (11.12)	Loni GZB (11.88)	Loni GZB (12.88)	Loni GZB (15.06)	Loni GZB (8.75)	Vikas sadan, GGN (6.35)	Vikas sadan, GGN (8.11)	Karnal, HRY (8.33)	Karnal, HRY (9.47)	Panipat, HRY (8.46)	Panipat, HRY (12.13)	Sirifort, Delhi (13.70)
Loni GZB (9.98)	Sector 51 GGN (9.08)	Sector 51 GGN (9.21)	Sector 51 GGN (7.63)	Palwal, HRY (5.51)	Sector 125, Noida (5.92)	Karnal, HRY (5.69)	Vikas sadan, GGN (7.63)	Panipat, HRY (5.93)	Mujaffar-nagar, UP (6.40)	Mujaffar-nagar, UP (5.04)	Jind, HRY (9.80)
Shadipur, Delhi (8.25)	Jind, HRY (6.67)	Panipat, HRY (7.27)	Vikas sadan, GGN (5.90)	Vikas sadan, GGN (5.96)	Palwal, HRY (5.38)			Vikas sadan, GGN (6.67)	Sirifort, Delhi (6.20)	Shadipur, Delhi (6.02)	Shadipur, Delhi (6.73)
Jind, HRY (7.45)	Sirifort, Delhi (6.18)	Charkhi dadri, HRY (5.73)	Sector 125, Noida (5.08)	Sector 125, Noida (6.49)	Sector 51 GGN (5.16)				Jind, HRY (6.10)	Karnal, HRY (7.23)	Chandni chowk, Delhi (6.55)
Charkhi dadri, HRY (6.39)	Vikas sadan, GGN (6.16)	Vikas sadan, GGN (5.66)							Loni GZB (5.82)	Sirifort, Delhi (10.36)	Sector 51, GGN (6.48)
Okhla, Delhi (5.57)	Charkhi dadri, HRY (5.08)	Jind, HRY (5.49)							Jind, HRY (9.79)	Jind, HRY (9.79)	Palwal, HRY (6.28)
Anand vihar, Delhi (5.53)		Gwal pahadi, GGN (5.03)								NSIT Dwarka (5.00)	Charkhi dadri, HRY (6.18)
Sector 51 GGN (5.48)										Sector 125, Noida (5.71)	Loni GZB (5.69)
Vikas sadan, GGN (5.38)										Palwal, HRY (6.34)	Mujaffarnagar, UP (5.24)
Sector 11 FBD (5.29)										Loni GZB (6.31)	Okhla, Delhi (5.02)



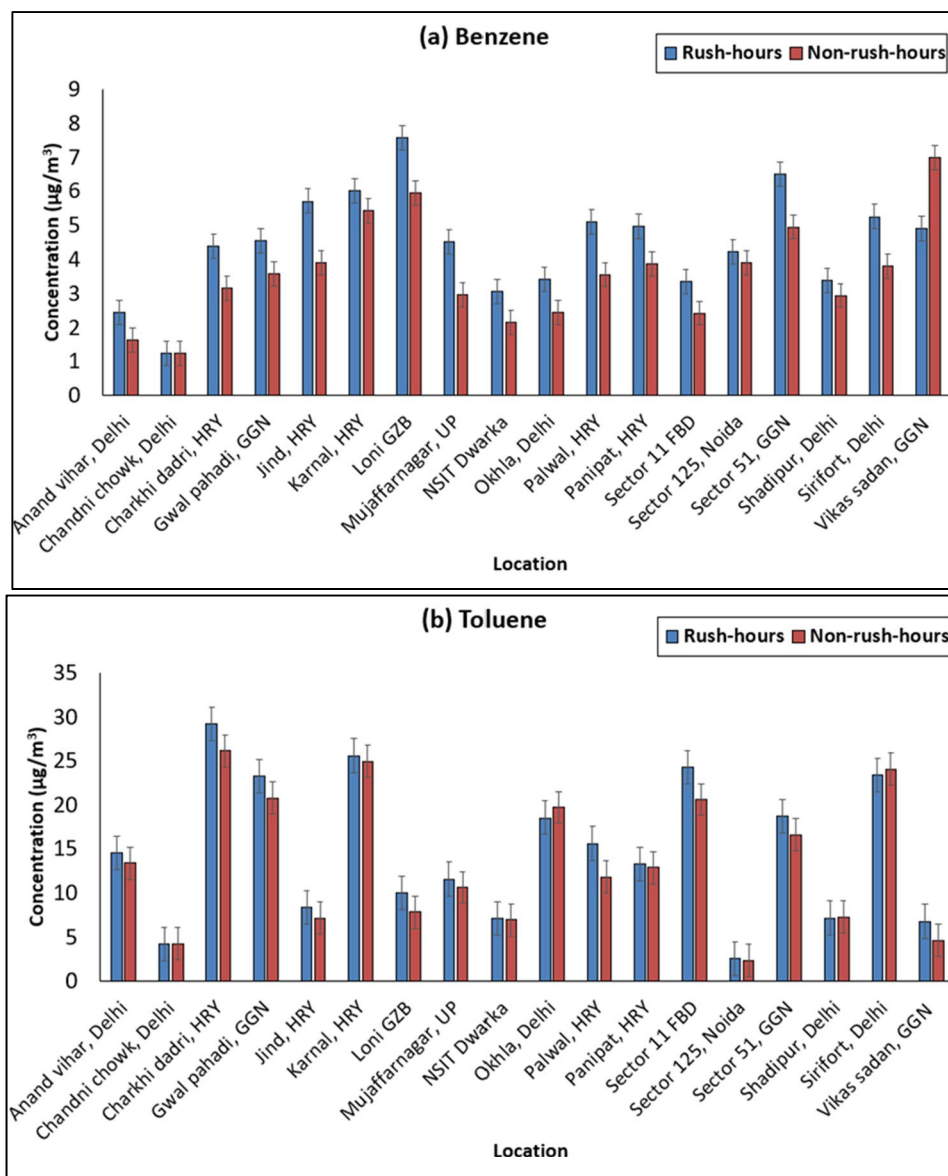
**Fig. 2** Effect of PBL and wind direction on study area **(a)**. Winters (DJF) **(b)**. Summers (MAM) **(c)**. Monsoon (JJA) **(d)**. Post monsoon (SON)

on the map. The higher PBL and increased wind speeds during these seasons promote dispersion of benzene. This is primarily due to a higher ventilation coefficient in summer and monsoon compared to post-monsoon and winter. However, high benzene concentrations can still occur in summer if emissions are high and wind speeds are low. This is observed in the Loni area, which is heavily industrialized and experiences significant vehicular pollution. Similar high summer benzene levels are noted in Sector 51 in Gurgaon and Sector 125 in Noida, primarily due to vehicular pollution. According to the Delhi Statistical Handbook (2023), there are 12 million registered vehicles in the region, with 3.38 million being private cars. Semi-urban areas such as Panipat, Charkhi Dadri, and Palwal also show high benzene concentrations, attributed to agricultural transport (tractors, trucks), vehicular pollution, and industrial activities,

including oil refineries. The absence of strict threshold limit rules for high-polluting industries and the non-application of BSVI vehicle standards in these cities, which are slightly distant from Delhi, contribute to elevated benzene levels in these areas. Additionally, during winter, wind direction predominantly towards the north and northeast contributes to pollution accumulation in these hotspot areas within Delhi NCR. The plot supports the data in Table 2, which shows that the highest pollution hotspots occur primarily during the post-monsoon and winter seasons.

Variations in the levels of benzene and toluene during rush hours (peak office time) and off-peak hours (non-rush) are shown in Fig. 3 (a, b). It can be seen that the average of benzene and toluene in the peak period is between 2.44–7.56 and 2.5–29.15  $\mu\text{g}/\text{m}^3$  respectively. The concentration range during off peak hours (non-rush hours) is 1.62–6.98, and

**Fig. 3** Rush and non-rush hours concentrations of benzene and toluene at Hotspot areas



2.31–26.11  $\mu\text{g}/\text{m}^3$  respectively. The benzene content in the peak period is 0.08–0.5 times that in the non-rush hours. The ratio of gasoline peak hours (rush) to off peak (non-rush) hours is highest in Muzaffarnagar, UP, an important Indian city for sugar, steel and paper industries. Likewise, the toluene content at the peak time is 0.19–0.08 times that of the off-peak hours. The ratio of toluene peak to off peak hours with the highest activity is at Vikas Sadan, Gurugram, Haryana, indication of high vehicular pollution. The results indicate that toluene concentrations are consistently higher than benzene at various locations. This is primarily due to the broader range of sources for toluene, such as vehicular emissions, industrial activities, and the production of paints, paint thinners, adhesives, and chemical intermediates. In contrast, benzene mainly originates from vehicular emissions (particularly from petrol and diesel engines) and industrial processes like oil refineries and chemical manufacturing. Toluene, with no specific emission limits set by national authorities, exhibits a shorter atmospheric lifetime due to higher reactivity, whereas benzene, less reactive, persists longer in the atmosphere (Cui et al. 2022). This persistence contributes to sustained high pollutant levels during both peak and off-peak hours in urban hotspots, highlighting the need for targeted emission control strategies to mitigate their environmental and health impacts effectively.

### Toluene to benzene ratio and factor analysis

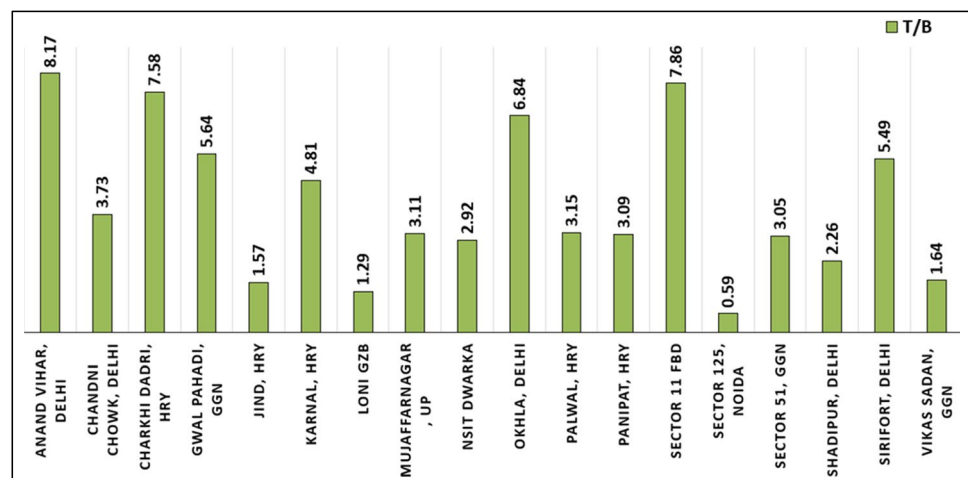
This study used toluene/benzene ratios and principal component analysis (PCA) to determine the possible sources of these compounds in the ambient air. The T/B ratio varies among sources due to their unique chemical profiles (Do et al. 2011; Liu et al. 2009; Gros et al. 2007; Hellen et al. 2003). For instance, gasoline emissions are characterized by a higher T/B ratio than those from industrial activities. The study focused on the T/B ratio, particularly in areas identified as pollution hotspots, and presented the findings in

Fig. 4. A T/B ratio nearing one suggests emissions primarily from vehicular traffic, with higher ratios observed closer to emission sources (Garg et al. 2019; Rad et al. 2014). The T/B ratio ranged from 0.59 to 8.17, with the lowest at Sector 125, Noida, and the highest at Anand Vihar, Delhi. The elevated T/B ratio at Anand Vihar points to significant vehicular emissions, likely from the numerous diesel buses operating out of the interstate bus terminal, with toluene being the predominant Volatile Organic Compound (VOC) emitted by diesel engines (Kim and Choi 2020). The T/B ratios reported in this study align with those from other international studies, indicating similar vehicular pollution sources. For example, T/B ratios of 3.6 in Hanoi, 6.9 in Belgium, and 2.3 in Ethiopia were reported, underscoring the global prevalence of vehicular emissions as a primary source of toluene and benzene (Stewart et al. 2021).

Principal Component Analysis (PCA) was applied to identify the primary sources of air pollution, following the methodology outlined by Cruz et al. (2020). Factor Analysis (FA) was used to organize the data into a correlation matrix, which facilitated a clearer understanding of the contributing factors. Factors were considered statistically significant if they had eigenvalues exceeding 1.00 and factor scores above 0.5. Using XLSTAT software, PCA was performed to determine the factor loadings for the three most polluted sites identified as hotspots.

As shown in Table 3, the results of the PCA indicated that three factors explained 65.72% of the total variance in the data. The first factor alone accounted for 30.45% of this variance and is strongly associated with high levels of toluene, benzene, and  $\text{NO}_2$  at Vikas Sadan, Gurugram, with loadings greater than 0.72. Notably, even higher loadings for toluene and benzene were observed at Loni Ghaziabad and Sirifort, Delhi, exceeding 0.92. The highest loading value, 0.929, was recorded for benzene and toluene at Loni Ghaziabad. This indicates that both vehicular traffic and industrial activities significantly contribute to air pollution at this

**Fig. 4** Toluene to benzene ratio at hotspot areas





**Table 3** PCA of pollutants & met parameters at top three hotspot areas

Factor Loadings	Vikas Sadan, Gurugram			Sirifort, Delhi			Loni, Ghaziabad	
	<i>F1</i>	<i>F2</i>	<i>F3</i>	<i>F1</i>	<i>F2</i>	<i>F3</i>	<i>F1</i>	<i>F2</i>
<i>Toluene</i>	<b>0.78</b>	-0.10		<b>0.94</b>			<b>0.92</b>	-0.13
<i>Benzene</i>	<b>0.76</b>	0.13		<b>0.92</b>			<b>0.92</b>	
<i>NO<sub>2</sub></i>	<b>0.72</b>			0.21	-0.55	<b>0.55</b>	0.12	-0.78
<i>O<sub>3</sub></i>	0.28	<b>0.62</b>	<b>0.26</b>	0.16	<b>0.83</b>	0.11	0.14	<b>0.74</b>
<i>WS</i>			<b>0.94</b>	-0.23	0.29	<b>0.66</b>	-0.17	<b>0.77</b>
<i>WD</i>	-0.14	<b>0.82</b>	-0.23			-0.54	<b>0.51</b>	

site. The presence of small- and large-scale manufacturing industries upwind from the city, combined with import and export activities involving light and heavy transportation, the proximity of the Dadri thermal power plant, and nearby petrol and diesel fueling stations, all result in elevated benzene and toluene concentrations in the area. (Behnami et al. 2023). Conversely, at Sirifort Road, Delhi, and Vikas Sadan, Gurugram, the presence of NO<sub>2</sub> along with benzene and toluene implicates that vehicular emissions are a major source of pollution. The study also indicates a correlation between NO<sub>2</sub> and ozone levels across different sites. At Vikas Sadan, a high concentration of NO<sub>2</sub> correlates with a lower ozone concentration, as evidenced by a factor loading of 0.623. Conversely, at Sirifort and Loni, lower NO<sub>2</sub> levels are associated with higher ozone concentrations. This suggests that in these areas, NO<sub>2</sub> rapidly transforms into ozone due to its short atmospheric lifespan. Additionally, the presence of high benzene and toluene concentrations contributes to ozone formation through reactions with NO<sub>2</sub>. The appropriate benzene to toluene ratios at these sites indicate significant ozone pollution in conjunction with benzene and toluene, whereas Vikas Sadan, Gurugram, is primarily affected by NO<sub>2</sub> pollution, along with benzene and toluene presence.

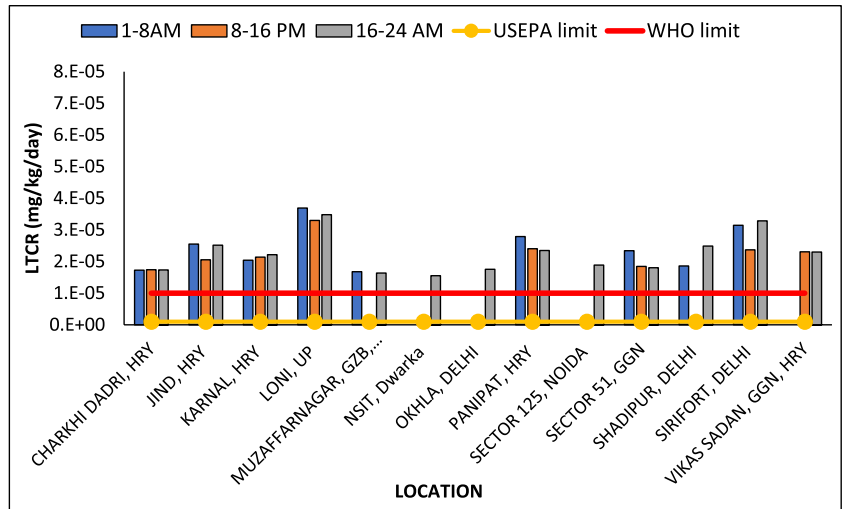
### Carcinogenic and non-carcinogenic risk assessment

This investigation assessed the potential health risks posed by benzene, aiming to understand the persistent outcomes of being exposed to benzene, which may result in cancer and a range of other negative health impacts on individuals (Mohammadi et al. 2020). The study computed the average daily exposure levels (E) (mg/kg/day) to inhaled benzene in two different groups (adults and children). The assumed exposure duration was 08 h/day for adults and children both (USEPA 1998, 2010, Masih et al. 2016). The LTCR's acceptable threshold for both adults and children stands at  $1 \times 10^{-6}$ , following USEPA guidelines, while the WHO's threshold is  $1 \times 10^{-5}$ . According to Sexton et al. (2007), the cancer risk is divided into three levels. Definitive risk: LTCR exceeds  $1.0 \times 10^{-4}$ , Probable risk: LTCR ranges between  $1 \times 10^{-5}$  and  $1 \times 10^{-4}$ , and Possible risk: LTCR falls between  $1 \times 10^{-6}$  and  $1 \times 10^{-5}$ . The findings revealed

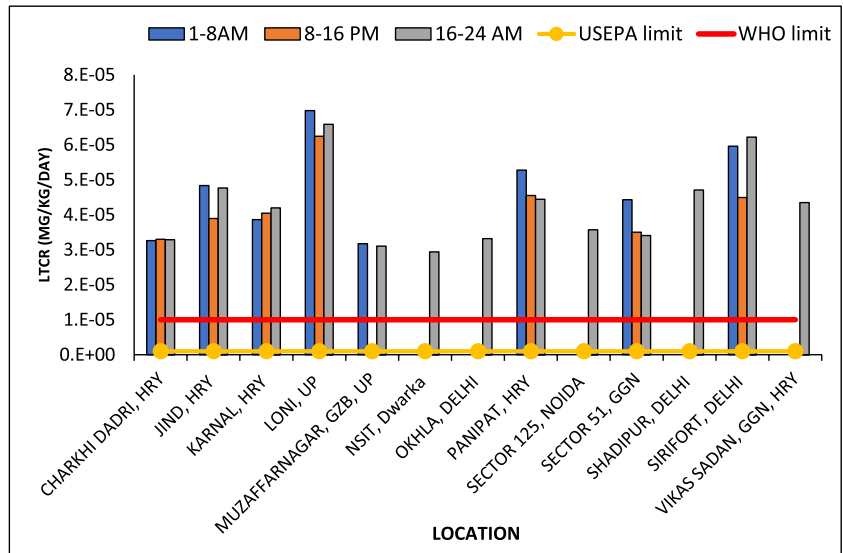
that, the maximum average daily exposure levels for adults were  $2.41 \times 10^{-3}$ ,  $2.51 \times 10^{-3}$ , and  $2.27 \times 10^{-3}$  mg/kg per day for 1–8 AM, 8–16 PM, and 16–24 AM respectively at Loni area of Ghaziabad respectively. While children had average daily exposure levels of  $1.27 \times 10^{-3}$ ,  $1.14 \times 10^{-3}$ , and  $1.20 \times 10^{-3}$  mg/kg/day for 1–8 AM, 8–16 PM, and 16–24 AM respectively at Loni area of Ghaziabad respectively. The LTCR values (cancer risk) for both adults & children ranged from  $3.30 \times 10^{-5}$  to  $6.98 \times 10^{-5}$ , exceeding the USEPA guidelines limit ( $1 \times 10^{-6}$ ) and the World Health Organization limit ( $1 \times 10^{-5}$ ). The study determined that individuals living in hotspot areas are likely at probable risk of cancer due to benzene exposure. It was observed that the Lifetime Cancer Risk (LTCR) was higher for children than for adults across all hotspot areas and at all times, especially in the morning (1–8 am) and evening to night hours (16–24 pm), as illustrated in Fig. 5. The elevated risk observed in children could be due to their smaller body mass relative to adults, which leads to a higher relative exposure when considering the dose per body weight, as exposure is inversely related to body weight.

The Hazard Quotient (HQ), commonly referred as non-cancer risk index, provides an estimate of the likelihood of developing non-cancerous health problems due to air pollutants. HQ values greater than 1 indicate that continuing exposure can lead to cardiovascular, and respiratory illness, while values below 1 are considered acceptable (Baberi et al. 2022; Dehghani et al. 2018; Garg et al. 2018; Zhang et al. 2012). The study found that non-carcinogenic risks such as dizziness, weakness, fatigue, nausea, and irritation of the eyes, skin, and respiratory tract due to benzene exposure remained significantly high (above 1) for the population in all hotspot areas, as shown in Fig. 6. The maximum HQ value i.e., 3.93 for benzene exposure was found at Loni, Ghaziabad, and the minimum was found at NSIT Dwarka, Delhi i.e., 1.37. These results suggest that the long-term benzene concentrations in the study area are associated with an increased danger of developing cardiovascular and respiratory diseases. This research concluded that the individual HQ values for benzene, were above the acceptable limits, indicating a risk of non-cancerous illness from inhalation exposure. The study identifies high LTCR and HQ values

**Fig. 5** Life time cancer risk (LTCR) at hotspot areas during different time intervals for adults (a) and children (b)

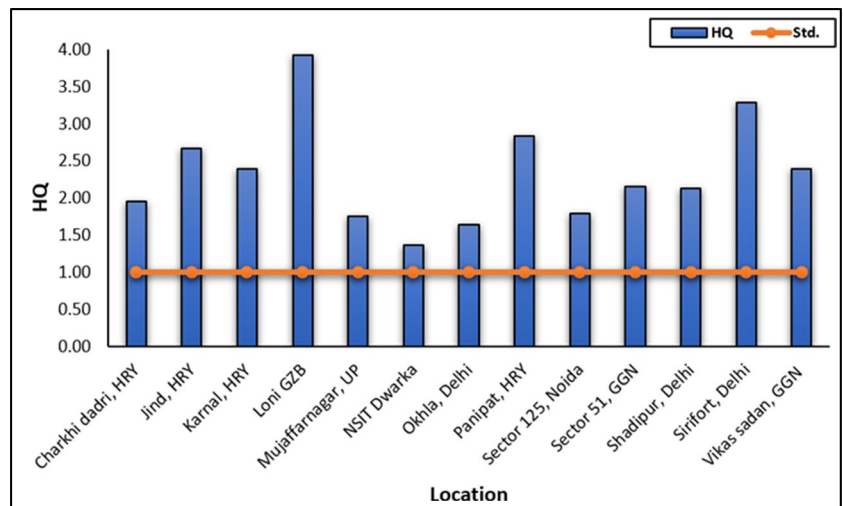


(a)



(b)

**Fig. 6** Hazard Quotient (HQ) of benzene & toluene at hotspot areas



of benzene raising concern for the population, particularly children during all the time in a day.

### Ozone production potential of benzene & toluene

The study examines the role of volatile organic compounds (VOCs) in O<sub>3</sub> production through photochemical reactions. Ozone Formation Potential (OFP) is a metric used to estimate the capability of VOCs to produce ozone in the urban atmosphere. This research predicted the OFP for various hotspots in the Delhi NCR region, presenting the findings in a Table 4. The Maximum Incremental Reactivity (MIR) coefficients for benzene and toluene are 0.72 and 4.00, respectively, which suggests that toluene is a more significant contributor to ozone formation. However, the Ozone Formation Potential (OFP) is not solely influenced by the Maximum Incremental Reactivity (MIR) coefficient; the actual concentration levels of Volatile Organic Compounds (VOCs) in the ambient air also plays a significant role.

Elevated concentrations of volatile organic compounds (VOCs) can lead to an increase in secondary aerosol formation (Goel et al. 2024). The average OFP values for benzene and toluene in the hotspot areas are detailed in the Table 4, with the highest toluene concentration at Charkhi Dadri, Haryana ( $29.65 \pm 2.26 \mu\text{g}/\text{m}^3$ ), followed by Karnal (Haryana) and the highest benzene concentration at Loni Ghaziabad ( $7.3 \pm 0.8 \mu\text{g}/\text{m}^3$ ) followed by Sector 51, Gurugram. The trend of toluene exceeding benzene was consistent

across all hotspots except for Sector 125, Noida. The total OFP levels were particularly high at Charkhi Dadri, surpassing the World Health Organization's air quality guidelines of  $120 \mu\text{g}/\text{m}^3$ . The findings indicate that toluene contributes significantly to ozone formation, which is consistent with similar studies conducted in other cities (Shan et al. 2023; Feng et al. 2018). Ozone is recognized as a harmful air pollutant due to its various adverse effects on human health, including respiratory issues and the potential to reduce lung capacity (Holm and Balmes 2022; Pinthong et al. 2022). High OFP levels could result in a range of respiratory symptoms and have been linked to premature deaths in studies around the world (Wu et al. 2022; Kim et al. 2020).

The ozone formation potential (OFP) of NO, NO<sub>2</sub>, benzene, and toluene was also analyzed across different time intervals: 0–8 am, 9–16 pm, and 17–23 pm. The data indicate that nighttime chemistry involving NO and benzene contributes to ozone formation as shown in Fig. 7. As sunlight increases in the morning, the formation of ozone is primarily driven by NO, followed by benzene, toluene, and NO<sub>2</sub>. NO<sub>2</sub> rapidly photolyzes in sunlight (wavelength  $\geq 343 \text{ nm}$ ) to produce NO and atomic oxygen, which then reacts with O<sub>2</sub> to form ozone (Kaushik and Das 2023; Berezina et al. 2020; Han et al. 2011).

During the evening (6–7 pm), the chemistry shifts, and NO becomes more prominent in forming ozone. VOCs act as catalysts for ozone formation during the morning and afternoon under UV-A radiation. However, in the evening,

**Table 4** Ozone formation Potential of Benzene & Toluene at different areas of Delhi NCR (Hotspots)

Hotspot Areas	Benzene			Toluene			Total OFP ( $\mu\text{g}/\text{m}^3$ )
	MEAN	SD	OFP	MEAN	SD	OFP	
Anand vihar, Delhi	2.53	0.55	1.82	20.80	6.36	83.20	85.02
Chandni chowk, Delhi	1.31	0.09	0.94	4.90	0.72	19.60	20.54
Charkhi dadri, HRY	3.95	0.51	2.84	<b>29.65</b>	2.26	<b>118.60</b>	<b>121.44</b>
Gwal pahadi, GGN	4.08	0.41	2.94	22.90	1.50	91.60	94.54
Jind, HRY	5.51	0.91	3.97	8.54	0.87	34.16	38.13
Karnal, HRY	5.64	0.34	4.06	26.97	1.75	107.88	111.94
Loni GZB	<b>7.30</b>	0.80	<b>5.26</b>	9.37	0.95	37.48	42.74
Mujaffarnagar, UP	4.05	0.57	2.92	12.48	2.06	49.92	52.84
NSIT Dwarka	3.36	0.77	2.42	9.84	3.14	39.36	41.78
Okhla, Delhi	3.73	0.83	2.69	25.36	7.08	101.44	104.13
Palwal, HRY	4.70	0.67	3.38	14.73	1.84	58.92	62.30
Panipat, HRY	4.57	0.43	3.29	14.01	0.99	56.04	59.33
Sector 11 FBD	3.10	0.46	2.23	24.10	2.28	96.40	98.63
Sector 125, Noida	4.61	0.78	3.32	2.73	0.46	10.92	14.24
Sector 51, GGN	6.64	1.36	4.78	19.96	3.03	79.84	84.62
Shadipur, Delhi	4.10	1.05	2.95	9.22	2.13	36.88	39.83
Sirifort, Delhi	5.25	0.80	3.78	28.54	5.06	114.16	117.94
Vikas sadan, GGN	5.47	0.93	3.94	8.68	3.05	34.72	38.66
min	1.31	0.09	0.94	2.73	0.46	10.92	14.24
max	7.30	1.36	5.26	29.65	7.08	118.60	121.44

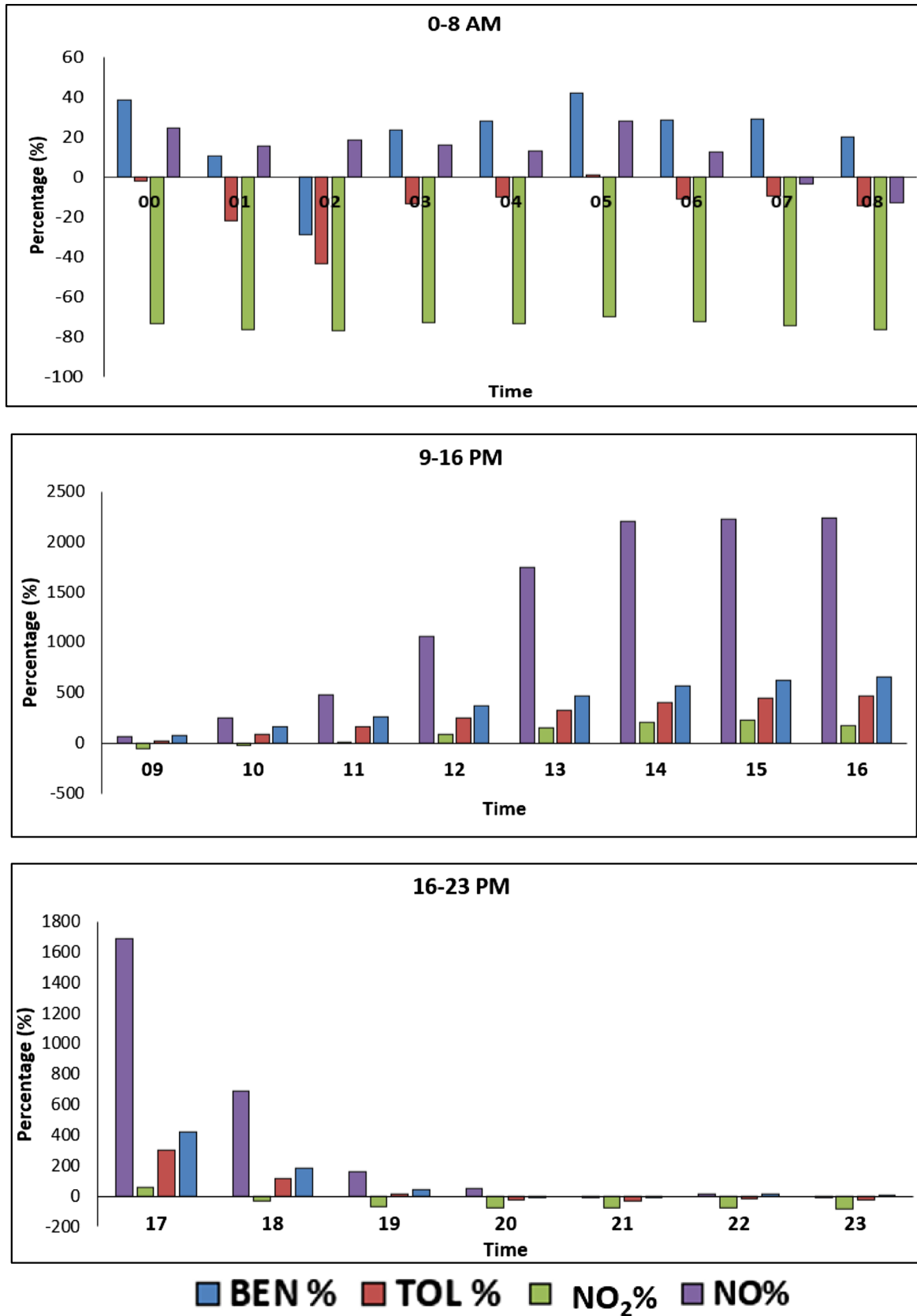


Fig. 7 Ozone formation percentage of NO, NO<sub>2</sub>, benzene and toluene

reduced UV-A radiation leads to higher VOC concentrations and lower ozone levels (Lefohn et al. 2018). In areas with high NO emissions, ozone formation is limited due to NO<sub>x</sub> titration, where NO breaks down ozone into O and O<sub>2</sub>. Thus, ozone levels depend on the transport of NO<sub>2</sub> and VOCs to areas with optimal concentration ratios and sufficient sunlight for ozone production.

## Conclusion

This study comprehensively assessed benzene and toluene emissions in Delhi NCR, their health risks, and their contribution to ozone formation. It identified eighteen hotspot areas across Delhi, Haryana, and Uttar Pradesh where benzene levels exceeded the national safe limit of 5 µg/m<sup>3</sup>. Seasonal and meteorological influences, such as lower planetary boundary layer (PBL) height and wind speeds during winter and post-monsoon seasons, contributed to higher benzene levels due to pollutant trapping, with traffic emissions being a major source, especially during rush hours. Health risk assessments indicated that benzene exposure pose significant risks for residents in these hotspot areas, exceeding recommended limits. The non-cancerous health risk (HQ) for benzene was also above 1, indicating potential respiratory and cardiovascular issues, with children at higher risk due to lower body weight. Toluene was identified as a more significant contributor to ozone formation compared to benzene, owing to its higher Maximum Incremental Reactivity (MIR) value. Elevated VOC concentrations, particularly toluene, led to high Ozone Formation Potential (OFP) levels, exceeding WHO air quality guidelines in some areas and posing a risk for respiratory problems. Overall, the study highlights the concerning levels of benzene and toluene in Delhi NCR and their detrimental impact on public health and air quality. It underscores the need for stricter emission control measures, the promotion of cleaner fuels and technologies, and strategic urban planning to mitigate these issues. Further research is recommended to explore additional mitigation strategies and to assess the effectiveness of existing control measures.

**Acknowledgements** The authors would like to thank CSIR-NPL, Academy of Scientific and Innovative Research (AcSIR), and Late Dr. Chhemendra Sharma for their encouragement and support. We also wish to acknowledge the Central Pollution Control Board (CPCB, India) for the online availability of the data.

**Author contributions** Nancy Kaushik: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization; A.K Mishra: Review & editing; Rupesh M. Das: Validation, Supervision.

**Funding** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

**Data availability** The datasets analysed during the study are available on the *Central Pollution Control Board website* (<https://app.cpcbcr.com/ccr/#/login> (CPCB INDIA)).

## Declarations

**Ethics approval** This is an observational study. No ethical approval is required.

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

**Consent for publication** The authors affirm to publish this study.

**Competing Interest** The authors have no relevant financial or non-financial interests to disclose.

## References

- Agency for Toxic Substances and Disease Registry (ATSDR) (2005) Toxicological profile for benzene; Atlanta, GA, USA
- Baberi Z, Azhdarpoor A, Hoseini M, Baghapour M, Derakhshan Z, Giannakis S (2022) Monitoring benzene, toluene, ethylbenzene, and xylene (BTEX) levels in mixed-use residential-commercial buildings in Shiraz, Iran: Assessing the carcinogenicity and non-carcinogenicity risk of their inhabitants. *Int J Environ Res Public Health* 19:723. <https://doi.org/10.3390/ijerph19020723>
- Behnami A, Jafari N, Benis KZ, Fanaei F, Abdollahnejad A (2023) Spatio-temporal variations, ozone and secondary organic aerosol formation potential, and health risk assessment of BTEX compounds in east of Azerbaijan Province, Iran. *Urban Climate* 47:101360. <https://doi.org/10.1016/j.uclim.2022.101360>
- Berezina E, Moiseenko K, Skorokhod A, Pankratova NV, Belikov I, Belousov V, Elansky NF (2020) Impact of VOCs and NO<sub>x</sub> on ozone formation in Moscow. *Atmosphere* 11(11):1–16. <https://doi.org/10.3390/atmos11111262>
- Carter WP (1990) A detailed mechanism for the gas-phase atmospheric reactions of organic compounds. *Atmos Environ* 24:481–518
- Carter WP (1994) Development of ozone reactivity scales for volatile organic compounds. *J Air Waste Manage Assoc* 44:881–899
- Carter WP (2010) Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications. California Air Resources Board Contract 07:339
- Caselli M, de Gennaro G, Marzocca A, Trizio L, Tutino M (2010) Assessment of the impact of the vehicular traffic on BTEX concentration in ring roads in urban areas of Bari (Italy). *Chemosphere* 81:306–311
- Central Pollution Control Board (CPCB) (2009) Revised national ambient air quality standards. NAAQS notification dated 18th November
- Chandra BP, Sinha V (2016) Contribution of post-harvest agricultural paddy residue fires in the N.W. Indo-Gangetic Plain to ambient carcinogenic benzenoids, toxic isocyanic acid and carbon monoxide. *Environ Int* 88:187–197. <https://doi.org/10.1016/j.envint.2015.12.025>
- Cruz LPS, Santos DF, dos Santos IF, Gomes ÍVS, Santos AVS, Souza KSPP (2020) Exploratory analysis of the atmospheric levels of BTEX, criteria air pollutants and meteorological parameters in a tropical urban area in Northeastern Brazil. *Microchem J* 152:104265
- Cui L, Wu D, Wang S, Xu Q, Hu R, Hao J (2022) Measurement report: Ambient volatile organic compound (VOC) pollution in urban Beijing: characteristics, sources, and implications for pollution

- control. *Atmos Chem Phys* 22:11931–11944. <https://doi.org/10.5194/acp-22-11931-2022>
- Dehghani M, Fazlzadeh M, Sorooshian A, Tabatabaee HR, Miri M, Baghani AN et al (2018) Characteristics and health effects of BTEX in a hot spot for urban pollution. *Ecotoxicol Environ Saf* 155:133–143
- Delhi Statistical Handbook (DSH) (2023) Directorate of economics & statistics. Government of national capital territory of Delhi
- Do DH, Van Langenhove H, Walgraeve C, Hayleeyesus SF, De Wispelaere P, Dewulf J, Demeestere K (2011) Volatile organic compounds in an urban environment: a comparison among Belgium, Vietnam and Ethiopia. *Int J Environ Anal Chem* 93(3):298–314. <https://doi.org/10.1080/03067319.2011.620708>
- Feng R, Wang Q, Huang C, Liang J, Luo K, Fan J, & Zheng H (2018) Ethylene, xylene, toluene and hexane are major contributors of atmospheric ozone in Hangzhou, China, prior to the 2022 Asian Games. *Environ Chem Lett* 17. <https://doi.org/10.1007/s10311-018-00846-w>
- Garg A, Gupta NC, Tyagi S (2019) Study of seasonal and spatial variability among benzene, toluene, and p-xylene (BTP-X) in ambient air of Delhi, India. *Pollution* 5:135–146
- Garg A, Gupta NC, Tyagi S (2018) Levels of benzene, toluene, ethylbenzene, and xylene near a traffic-congested area of East Delhi. *Environ Claim J* <https://doi.org/10.1080/10406026.2018.1525025>
- Goel V, Tripathi N, Gupta M, Sahu LK, Singh V, Kumar M (2024) Study of secondary organic aerosol formation and aging using ambient air in an oxidation flow reactor during high pollution events over Delhi. *Environ Res* 251:118542. <https://doi.org/10.1016/j.envres.2024.118542>
- Gros V, Sciare J, Yu T (2007) Air-quality measurements in megacities: Focus on gaseous organic and particulate pollutants and comparison between two contrasted cities, Paris and Beijing. *Comptes Rendus Geosci* 339:764–774. <https://doi.org/10.1016/j.crte.2007.08.007>
- Han S, Bian H, Feng Y, Liu A, Li X, Zeng F, Zhang X (2011) Analysis of the relationship between O<sub>3</sub>, NO and NO<sub>2</sub> in Tianjin. *China Aerosol Air Qual Res* 11(2):128–139. <https://doi.org/10.4209/aaqr.2010.07.0055>
- Hellen H, Hakola H, Laurila T (2003) Determination of source contributions of NMHCs in Helsinki (60 N, 25 E) using chemical mass balance and the Unmix multivariate receptor models. *Atmos Environ* 37:1413. [https://doi.org/10.1016/S1352-2310\(02\)01049-X](https://doi.org/10.1016/S1352-2310(02)01049-X)
- Henze DK, Seinfeld JH, Ng NL, Kroll JH, Fu TM, Jacob DJ, Heald CL (2008) Global modeling of secondary organic aerosol formation from aromatic hydrocarbons: High- vs. low-yield pathways. *Atmos Chem Phys* 8(9):2405–2421. <https://doi.org/10.5194/acp-8-2405-2008>
- Holm SM, Balmes JR (2022) Systematic review of ozone effects on human lung function, 2013 through 2020. *Chest* 161(1):190–201. <https://doi.org/10.1016/j.chest.2021.07.2170>
- Hoque RR, Khillare PS, Agarwal T, Shridhar V, Balachandran S (2008) Spatial and temporal variation of BTEX in the urban atmosphere of Delhi. *India Sci Total Environ* 392:30–40
- Hosseinpour N, Sabeti Z, Aslani H, Benis KZ, Shakerkhatibi M, Najafloo A, Malekzadeh M, TayefehRahimian R (2024) Investigation of ambient BTEX concentrations along a bus rapid transit route in Tabriz: Spatio-temporal variations and health risk assessment. *Urban Climate* 54:101860. <https://doi.org/10.1016/j.uclim.2024.101860>
- International Agency for Research on Cancer (IARC) (2002) IARC monographs programme on evaluation of carcinogenic risks to humans
- Iyer US, Raj PE (2013) Ventilation coefficient trends in the recent decades over four major Indian metropolitan cities. *J Earth Syst Sci* 122:537–549. <https://doi.org/10.1007/s12040-013-0270-6>
- Kaushik N, Das RM (2023) Investigation of NO<sub>x</sub> and related secondary pollutants at Anand Vihar, one of the most polluted area of Delhi. *Urban Climate* 52:101747. <https://doi.org/10.1016/j.uclim.2023.101747>
- Kermani M, JonidiJafari A, Gholami M, Taghizadeh F, Masroor K, Abdolhanejad A, Shahsavani A, Fanaei F (2021) Characterisation of PM<sub>2.5</sub>-bound PAHs in outdoor air of Karaj megacity: the effect of meteorological factors. *International Journal of Environmental Analytical Chemistry* 103:3290–3308. <https://doi.org/10.1080/03067319.2021.1906425>
- Kim HY, Choi NJ (2020) Study on volatile organic compounds from diesel engine fueled with palm oil biodiesel blends at low idle speed. *Appl Sci* 10(14):4969. <https://doi.org/10.3390/app10144969>
- Kim BM, Park EK, LeeAn SY, Ha M, Kim EJ, Kwon H et al (2009) BTEX exposure and its health effects in pregnant women following the Hebei spirit oil spill. *J Prev Med Public Health* 42:96–103
- Kim SY, Kim E, Kim WJ (2020) Health Effects of Ozone on Respiratory Diseases. *Tuberc Respir Dis* 83:S6–S11. <https://doi.org/10.4046/trd.2020.0154>
- Kumar A, Singh BP, Punia M, Singh D, Kumar K, Jain VK (2014) Determination of volatile organic compounds and associated health risk assessment in residential homes and hostels within an academic institute, New Delhi. *Indoor Air* 24(5):474–483. <https://doi.org/10.1111/ina.12096>
- Lefohn AS, Malley CS, Smith L, Wells B, Hazucha M, Simon H, Naik V, Mills G, Schultz MG, Paoletti E, De Marco A, Xu X, Zhang L, Wang T, Neufeld HS, Musselman RC, Tarasick D, Brauer M, Feng Z, Gerosa G (2018) Tropospheric ozone assessment report: global ozone metrics for climate change, human health, and crop/ecosystem research. *Elementa* 6. <https://doi.org/10.1525/elementa.279>
- Liu JF, Mu YJ, Zhang YJ, Zhang ZM, Wang XK, Liu YJ, Sun ZQ (2009) Atmospheric levels of BTEX compounds during the 2008 Olympic Games in the urban area of Beijing. *Sci Total Environ* 408:109
- Masih A, Lall AS, Taneja A, Singhvi R (2016) Inhalation exposure and related health risks of BTEX in ambient air at different microenvironments of a terai zone in north India. *Atmos Environ* 147:55–66
- Mehta D, Hazarika N, Srivastava A (2020) Diurnal variation of BTEX at road traffic intersection points in Delhi, India: source, ozone formation potential, and health risk assessment. *Environ Sci Pollut Res* 27(10):11093–11104. <https://doi.org/10.1007/s11356-019-07495-8>
- Ministry of Labour & Employment, Government of India (2023) Acts & rules; section: hours of work
- Mohammadi A, Ghassoun Y, Löwner M-O, Behmanesh M, Faraji M, Nemati S, Toolabi A, Abdolhanejad A, Panahi H, Heydari H, Miri M (2020) Spatial analysis and risk assessment of urban BTEX compounds in Urmia, Iran. *Chemosphere* 246:125769. <https://doi.org/10.1016/j.chemosphere.2019.125769>
- National Capital Region Planning Board (2016) <https://ncrpb.nic.in/ncrconstituent.html>
- Petrus M, Popa C, Bratu A-M (2024) Determination of ozone concentration levels in urban environments using a laser spectroscopy system. *Environments* 11(1):9. <https://doi.org/10.3390/env11010009>
- Pinthong N, Thepanondh S, Kondo A (2022) Source identification of VOCs and their environmental health risk in a petrochemical industrial area. *Aerosol Air Qual Res* 22:210064. <https://doi.org/10.4209/aaqr.210064>
- Praveen B, Talukdar S, Shahfahad et al (2020) Analyzing trend and forecasting of rainfall changes in India using non-parametrical and machine learning approaches. *Sci Rep* 10:10342. <https://doi.org/10.1038/s41598-020-67228-7>

- Rad HD, Babaei AA, Goudarzi G, Angali KA, Ramezani Z, Mohammadi MM (2014) Levels and sources of BTEX in ambient air of Ahvaz metropolitan city. *Air Qual Atmos Health* 7:515–524
- Ramírez N, Cuadras A, Rovira E, Borrull F, Marcé RM (2012) Chronic risk assessment of exposure to volatile organic compounds in the atmosphere near the largest Mediterranean industrial site. *Environ Int* 39(1):200–209. <https://doi.org/10.1016/j.envint.2011.11.002>
- Rizwan SA, Baridalyn N, Sanjeev KG (2013) Air pollution in Delhi: Its magnitude and effects on health. *Indian J Commun Med* 38(1):4–8
- Saha D, Soni K, Mohanan MN, Singh M (2019) Long-term trend of ventilation coefficient over Delhi and its potential impacts on air quality. *Remote Sens Appl Soc Environ* 15:100234. <https://doi.org/10.1016/j.rsase.2019.05.003>
- Sexton K, Linder SH, Marko D, Bethel H, Lupo PJ (2007) Comparative Assessment of Air Pollution-Related Health Risks in Houston. *Environ Health Perspect* 115(10):1388–1393. <https://doi.org/10.1289/ehp.10043>
- Shan D, Du Z, Zhang T, Zhang X, Cao G, Liu Z, Yao Z, Tang K, Liang S (2023) Variations, sources, and effects on ozone formation of VOCs during ozone episodes in 13 cities in China. *Front Environ Sci* 10:1388–1393. <https://doi.org/10.3389/fenvs.2022.1084592>
- Shukla K, Kumar P, Mann GS, Khare M (2020) Mapping spatial distribution of particulate matter using kriging and inverse distance weighting at supersites of megacity Delhi. *Sustain Cities Soc* 54:101997. <https://doi.org/10.1016/j.scs.2019.101997>
- Singh R, Gaur M, Shukla A (2016) Seasonal and Spatial Variation of BTEX in Ambient Air of Delhi. *J Environ Prot* 7:670–688. <https://doi.org/10.4236/jep.2016.75060>
- Stewart GJ, Nelson BS, Drysdale WS, Acton WJF, Vaughan AR, Hopkins JR, Dunmore RE, Hewitt CN, Nemitz E, Mullinger N, Langford B, Reyes-Villegas SE, Gadi R, Rickard AR, Lee JD, Hamilton JF (2021) Sources of non-methane hydrocarbons in surface air in Delhi, India. *Faraday Discuss* 226:409–431. <https://doi.org/10.1039/D0FD00087F>
- Tiwari V, Hanai Y, Masunaga S (2010) Ambient levels of volatile organic compounds in the vicinity of petrochemical industrial area of Yokohama, Japan. *Air Qual Atmos Health* 3(2):65–75
- USEPA (1997) Air risk assessment work plan. Air and radiation division, EPA, Washington, DC
- USEPA (1998) Integrated Risk Information System (IRIS). Available at. [www.epa.gov](http://www.epa.gov) US Environmental Protection Agency, Washington, DC.
- USEPA (2010) Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment, EPA 540-r-070-002). Office of Superfund Remediation and Technology Innovation Environmental Protection Agency, Washington, D.C.
- Wu H, Lu K, Fu J (2022) A time-series study for effects of ozone on respiratory mortality and cardiovascular mortality in Nanchang, Jiangxi Province, China. *Front Public Health* 10:864537. <https://doi.org/10.3389/fpubh.2022.864537>
- Zawacki M, Baker KR, Phillips S, Davidson K, Wolfe P (2018) Mobile source contributions to ambient ozone and particulate matter in 2025. *Atmos Environ* 188:129–141. <https://doi.org/10.1016/j.atmosenv.2018.04.057>
- Zhang Y, Mu Y, Liu J, Mellouki A (2012) Levels, sources and health risks of carbonyls and BTEX in the ambient air of Beijing. *China J Environ Sci* 24:124–130
- Zhang Z, Wang X, Zhang Y, Lü S, Huang Z, Huang X, Wang Y (2015) Ambient air benzene at background sites in China's most developed coastal regions: exposure levels, source implications and health risks. *Sci Total Environ* 511:792–800
- Zhu S, Yu H, Zhang Y, Zhang Y, & Kinnon MM (2022) Editorial: Air pollution and climate change: Interactions and co-mitigation. *Front Environ Sci* 10. <https://doi.org/10.3389/fenvs.2022.1105656>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.