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HEALTH RISK ASSESSMENT AND SOURCE APPORTIONMENT OF BLACK CARBON AEROSOLS IN EASTERN INDIAN INDUSTRIAL CITIES

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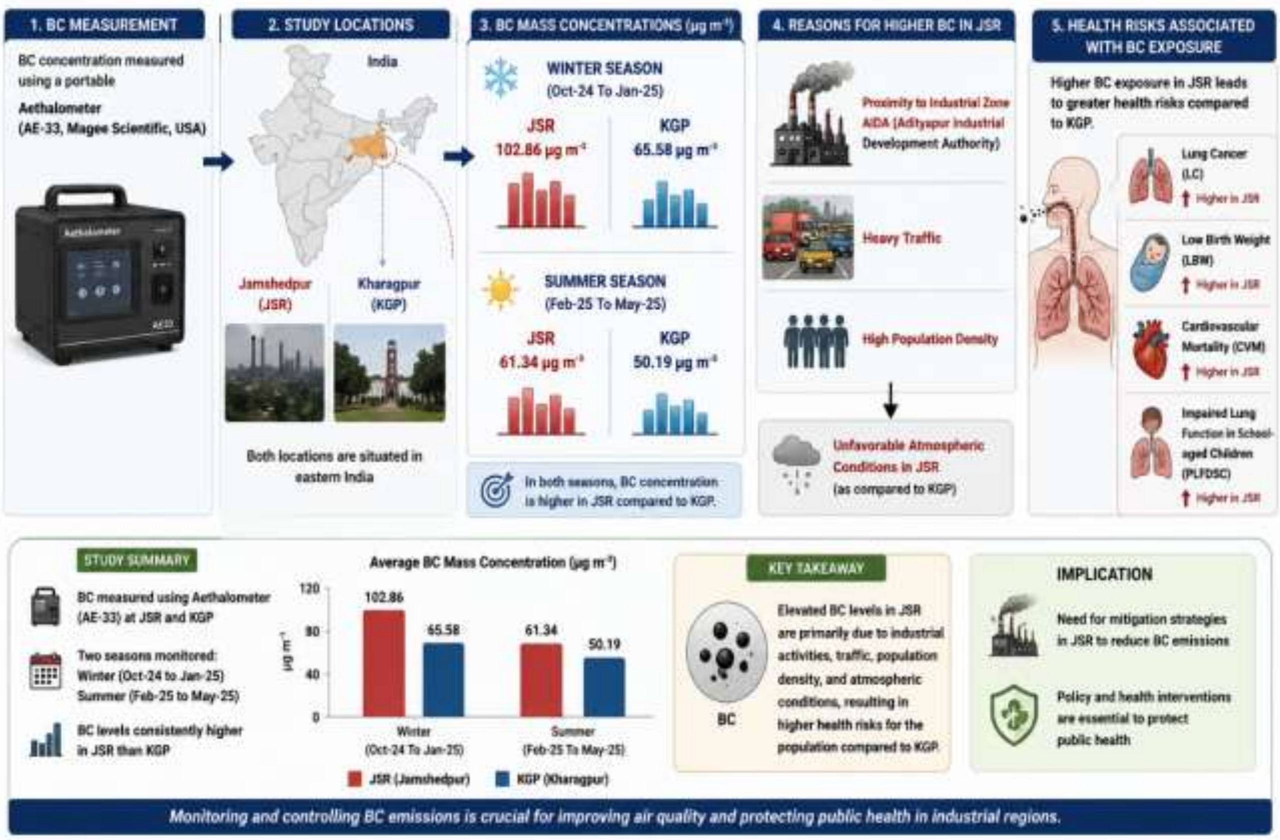
Graphical Abstract



ABSTRACT

The role of black carbon (BC) is vital in the assessment of health effects on individuals. Concentration of BC is measured by a portable aethalometer (AE-33, Magee Scientific, USA) at two distinct locations: the Jamshedpur (JSR) and the Kharagpur (KGP), both situated in eastern India. During study period BC aerosol mass concentrations measurement for winter season (Oct-24 To Jan-25) and Summer season (Feb-25 To May- 25) in JSR and KGP is measured. The averaged mean BC mass concentrations were noticed to be about 102.86 μgm^{-3} at JSR and 65.58 μgm^{-3} at KGP in the winter period. The averaged mean BC mass concentrations were noticed to be about 61.34 μgm^{-3} at JSR and 50.19 μgm^{-3} at KGP in the Summer Period. The elevated levels of BC concentrations in JSR were attributed to the proximity of an industrial zone, specifically AIDA (Adityapur Industrial Development Authority), along with heavy traffic and a high population density. Higher concentration of BC in JSR the atmospheric condition as compare to KGP. So health risk associated with BC exposure like lung cancer (LC), low birth weight (LBW), cardiovascular mortality (CVM), and impaired lung function in school-aged children (PLFDSC) were more in JSR as compare to KGP.

KEYWORDS: Aethalometer-33, Black carbon, Health risk assessment

1 INTRODUCTION

In the 21st century, air pollution in the environment has become a significant health issue. The fast growth of energy-consuming activities and biomass burning in India has resulted in dangerously elevated emissions of pollutants, which endanger both human health and the environment [1, 2]. Dependence on coal for energy generation is a significant contributor to the high levels of ambient black carbon (BC) within the country. The primary components of particulate matter are black carbon (BC), which consists of water-soluble inorganic ions such as Na^+, K^+, and Cl^-, and are influenced by emission sources as well as meteorological conditions [3]. Other notable constituents, such as sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+), predominantly stem from human endeavors [4].

Air pollution arises from both human activities and natural events that emit harmful substances into the atmosphere, posing risks to human health and the overall ecosystem. The challenge of air pollution is a critical issue on regional and global scales, influencing the economy, society, tourism, and health. Particulate matter (PM) is a key factor in adverse health outcomes, including respiratory diseases and cardiovascular problems, and is emitted from industrial activities, agricultural operations, and transportation [5].

The principal origins of black carbon encompass the incomplete burning of fossil fuels, the use of solid fuels for home cooking, the combustion of fuel in vehicles, biomass burning, and forest fires [6, 7]. It is discharged in conjunction with other products resulting from incomplete combustion, such as organic carbon, carbon monoxide, and several volatile organic-compounds. As a key element in particulate matter (PM), black carbon (BC) is acknowledged to pose serious health risks, such as an elevated likelihood of respiratory and cardiovascular illnesses. [5, 8, 6, 9]. Across urban landscapes worldwide, the prevalence of particulate pollution raises significant concerns, as investigations have confirmed correlations with respiratory ailments including asthma and a range of cardiopulmonary illnesses. [10]. The challenge of air pollution in India and other South Asian nations has gained worldwide recognition because of the South Asian haze, which is responsible for a considerable number of early deaths each year [11, 12, 13]. Confronting this rising issue requires extensive research to direct policy decisions and elevate public awareness regarding the scale and attributes of air pollution in both outdoor and indoor environments. The threat posed by particulate pollution is notably severe in urban locales worldwide, as investigations have connected it to respiratory issues like asthma and numerous cardiopulmonary illnesses [14, 15, 10].

Despite the fact that investigations into the composition and distribution of BC and PMx (particulate matter) have taken place across various parts of the Indo-Gangetic Basin, there is a notable lack of research in eastern India. Thus, an in-depth analysis of black carbon concentrations, including their health implications and emission sources, is vital for crafting effective environmental policies. This analysis concentrates on the variation and source characterization of black carbon aerosol, with a specific focus on the impact of biofuel and biomass combustion on urban air quality in eastern India.

2 MATERIALS AND METHODS

2.1 Study location site details and meteorology

This investigation aims to monitor and compare the levels of Black Carbon (BC) in Jamshedpur (JSR) and Kharagpur (KGP), both of which are strategically situated industrial cities in eastern India .(Fig. 1).

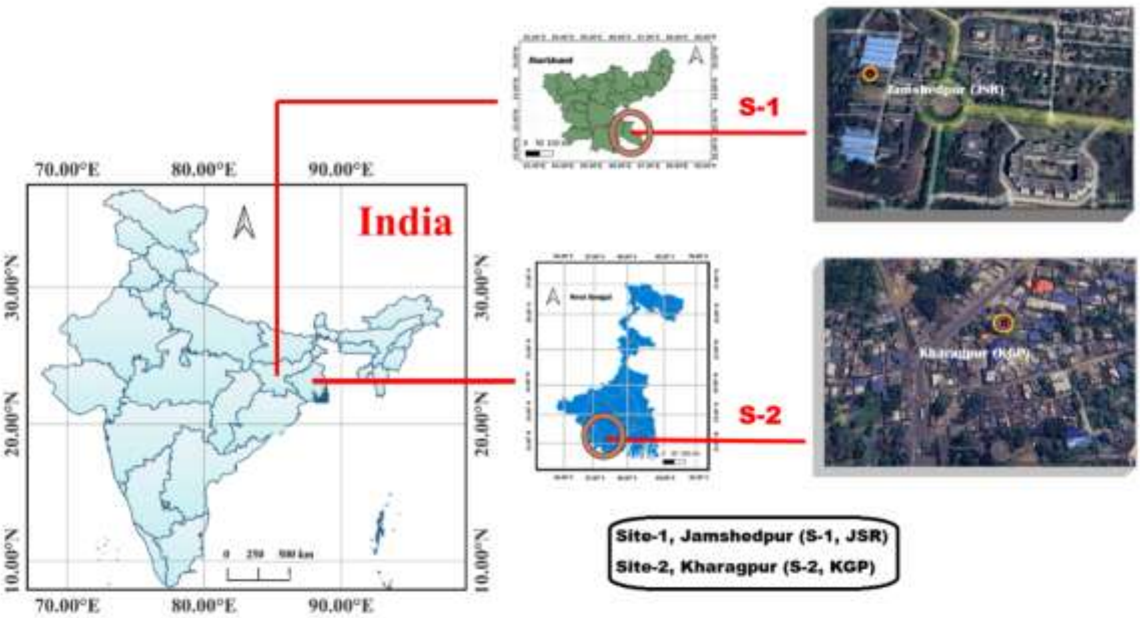


Fig. 1- Study area of the two Indian cities i.e., Jamshedpur (JSR) and Kharagpur (KGP)

Jamshedpur (JSR): Located in the southeastern region of Jharkhand (22° 80' N, 86° 20' E). Based on the 2011 census, its population was roughly 1.3 million, with a density of 6400 persons per km². Jamshedpur is recognized as a key industrial hub in eastern India, featuring major companies like Tata Steel, Tata Motors, and Cement Company, along with various small and medium-sized industries. These sectors, together with vehicle traffic and the combustion of coal, wood, and dung cakes, play a major role in the contribution of atmospheric pollutants, such as black carbon (BC). Furthermore, the city's highway system also influences regional emissions. Ambient air samples were gathered in Jamshedpur for the purposes of this study.

Kharagpur (KGP): In southern West Bengal (22.33° N, 87.32° E), Kharagpur stands out as a key industrial city. The projected population for 2023 is approximately 339,725 individuals. Kharagpur is known for its strong transportation network, which primarily consists of railways, roadways, and railway workshops. The West Bengal Industrial Development Corporation (WBIDC) is a major contributor to the industrial sector, presenting a wide array of industries. Additionally, ambient air samples were gathered in Kharagpur for comparative analysis.

2.2 Measurements of BC Concentration

An Aethalometer-33 device (model no. AE-33, made by Magie Scientific, Barkeley, USA) was utilized for the continuous real-time monitoring of black carbon (BC) mass concentration. Today, the AE-33 stands out as one of the advanced tools for measuring BC, as it computes BC concentration at seven various wavelength channels: 370 nm (BC1), 470 nm (BC2), 525 nm (BC3), 590 nm (BC4), 660 nm (BC5), 880 nm (BC6), and 940 nm (BC7). The Aethalometer's ability to capture a greater number of BC particles on the filter tap is characterized by maximum attenuation at a wavelength of 880 nm. This stands in contrast to other techniques such as melting reflectance, particle soot-absorption photometer (PSAP), and haze tape-sampling coefficient [16] , the Aethalometer model is a simple and effective way to measure ambient aerosols that include BC. This technique is contingent upon the attenuation of light caused by the substantial concentration of BC that is laid down on the filter spot. At two different sites i.e., Kharagpur and Jamshedpur, the air intake is carefully positioned on the rooftops. The air intake system draws in surrounding air at a specified flow rate of 5 LPM. Quartz filters were utilized during the sampling process to ensure optimal precision. The concentrations of BC mass were diligently tracked every 5 minutes. Numerous publications underscore the pronounced absorption of BC at 880 nm (BC6), suggesting that BC is dominant at this wavelength, whereas other components show negligible absorption [1].

2.3 Health-Risk Assessment

As a result of their small dimensions, particulate pollutants like black carbon (BC) can significantly penetrate human organs, leading to notable health risks. To elucidate these risks, this study draws a comparison between BC exposure and environmental tobacco smoke (ETS), building on the findings of earlier research. [17]. It has been estimated that the daily exposure to BC may equate to smoking about 14 cigarettes, a standard level commonly found in the United States and Western Europe. This corresponds with studies that show the health repercussions of BC are akin to the indirect impacts of cigarette smoke [18].

The evaluation of BC and ETS identifies three essential similarities: (a) both pollutants access the body through similar routes, (b) they exhibit comparable pollutant compositions, including gaseous compounds and suspended particles, and (c) both cause uncontrolled health effects [17]. This analysis explores the risks of BC exposure for residents situated near sampling sites in Jamshedpur (JSR) and Kharagpur (KGP), showing levels that are comparable to passive smoking. Van der Zee (2016) proposed a model aimed at assessing health risks from exposure to environmental tobacco smoke (ETS) identified four primary health effects: lung cancer (LC), low birth weight (LBW), cardiovascular mortality (CVM), and impaired lung function in school-aged children (PLFDSC) [17]. Additionally, these health problems have been correlated with exposure to biomass combustion (BC) [19].

Health risk assessments frequently employ relative risk ratios (RRs) to evaluate the health effects associated with exposure to ETS and BC aerosols. [20 , 17 , 21]. While RR estimations are continually refined, existing values for RR_{BC} and RR_{ETS} from comprehensive reviews provide a basis for evaluating potential health effects. Meta-analyses of concentration-response functions (CRFs) demonstrate the correlation between changes in BC levels and health risks. For instance, an increase of 1 $\mu g\ m^{-3}$ in BC concentration corresponds to health consequences comparable to passive smoking [22] The risk (R) is calculated as follows:

$\mathbf{R} = RR_{BC}/RR_{ETS} = [\ln (RR_{BC})/\Delta Concn]/ [\ln (RR_{ETS})/Assumed\ PSC]$ …….. (i)

Where,

- **RR_{BC}** represents the relative risk for a specific health condition due to BC exposure, and
- **RR_{ETS}** represents the relative risk from ETS exposure.
- **$[\ln (RR_{BC})/\Delta Concn]$** represent the total risks due to BC change by 1 $\mu g\ m^{-3}$
- **$[\ln (RR_{ETS})/Assumed\ PSC]$** represent the total risks due to ETS exposure for the assumed PSC per day.
- **ETS** represent Environmental tobacco smoke
- **PSC** represent Passive smoke from several cigarettes

These values are drawn from various studies [23]. The estimated number of passive smoking equivalents (PSC) differ depending on the health hazard. For PLFDSC, the assumed daily PSC count is around 9, while for newborns of non-smoking mothers, the assumed PSC values for CVM and LC are approximately 7. Similarly, adults facing LBW risks are estimated to have an equivalent PSC of 7 [22]. The equations below estimate the equivalent number of passive cigarettes per day (NPSC), representing passive smoking equivalence.

$N_{PSC} = \Delta BC \times R$ ……………. (ii)

And,

$\Delta BC = (BC_{REP} - BC_{BAK})$ ……………. (iii)

where,

- **BC_{REP}** represent the reported BC concentration
- **BC_{BAK}** represent the background BC concentration

2.4 Source Apportionment of Black Carbon

Black Carbon (BC) is derived from various sources, such as diesel engines, cooking, wood burning, dung cakes, coal, gasoline, vehicle oil, industrial waste, and agricultural waste. These sources are broadly categorized into Biomass Burning (BB) and Fossil Fuel Combustion (FF). The Aethalometer Model serves as an effective tool for measuring the contribution of each category, as it assesses carbonaceous aerosol (BC) levels through aerosol light absorption [24]. This model also incorporates parameters such as absorption exponents (α) and absorption Ångström exponents.

Other established techniques for source apportionment include the Chemical Mass Balance (CMB) method [25] , the Microtracer approach [26], Positive Matrix Factorization (PMF) [27] , the Radiocarbon method [28], specialized analytical techniques [29] , and Principal Component Analysis (PCA) [30]. Each of these techniques possesses its own advantages and drawbacks; however, the Aethalometer Model stands out for its ability to precisely identify BC sources. As noted by [29] , this model assigns BC sources using Ångström absorption coefficients (AAE) and differentiates between FF and BB emissions without the need for additional data.

The Chemical Mass Balance method is capable of distinguishing between general categories of BC sources; however, it may not encompass all contributors. The Macrotracer method approximates FF and BB emissions by relying on average emission factors. In contrast, specialized models assist in identifying residual BC from sources that are challenging to classify [29]. PMF, when applied to a similar data matrix before normalization, provides an objective interpretation of source contributions. This technique aids in recognizing emissions from sources such as wood burning, industrial processes (including the combustion of fossil fuels and coal), vehicle emissions, and the burning of petroleum products by investigating the absorption of light based on its wavelength. [31 , 32 , 8].

Two industrial cities, specifically the JSR site (S1) and KGP site (S2), have been acknowledged for their specific sources of black carbon emissions. Initially, measurements of black carbon concentrations were taken at two wavelengths—370 nm and 880 nm—to evaluate the distinct contribution of black carbon through the following formula:

%Contribution of BC = $(BC370 - BC880)/BC880$ ……………………… (iv)

This equation yields two possible outcomes:

• **Case I:** If the % contribution of BC is negative, it indicates that BC emissions primarily originate from liquid fuel combustion, i.e., fossil fuel burning (BC_{FF}) [33].

• **Case II:** If the % contribution of BC is positive, it suggests that emissions predominantly result from biomass burning (BC_{BB}), such as wood combustion, coal, forest fires, or stubble burning [34].

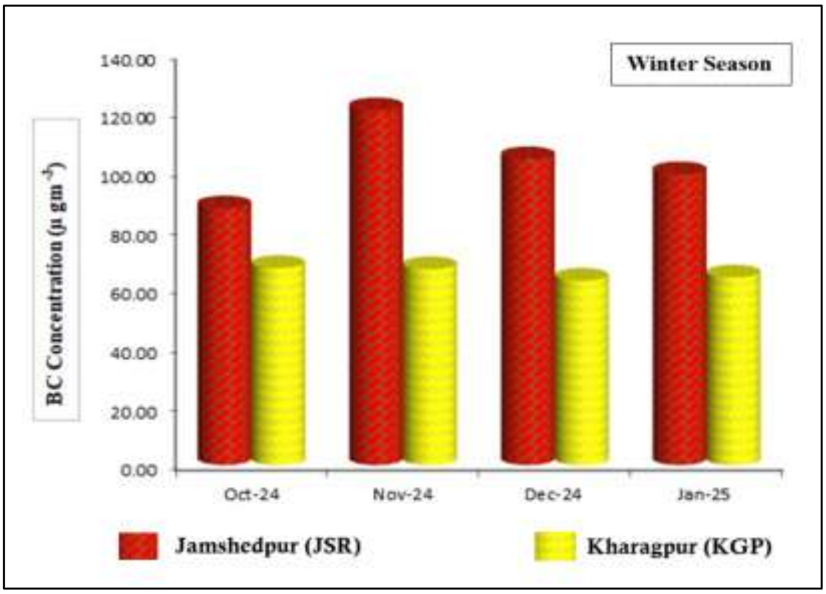
Numerous research studies have validated the efficacy of the Aethalometer Model, created by Magee Scientific, in precisely estimating black carbon emissions from both biomass combustion and fossil fuel sources. [35, 36 , 28].

3. RESULTS AND DISCUSSIONS

3.1 Variation of BC Concentration

BC aerosol mass concentrations measurement for winter season (Oct-24, Nov-24, Dec-24 and Jan-25) and summer season (Feb-25, Mar-25, Apr-25, and May- 25) in Jamshedpur (JSR) as shown in Table 1 and Fig 2. The averaged mean BC mass concentrations were noticed to be about 102.86 μgm^{-3} at JSR. Variations in monthly mean BC mass concentration during winter season in JSR, the monthly averaged concentration of BC mass concentration was noticed around 87.41 μgm^{-3}, 120.85 μgm^{-3}, 104.14 μgm^{-3} and 99.04 μgm^{-3} in October 2024, November 2024, December 2024 and January 2025 respectively. The averaged mean BC mass concentrations were noticed to be about 61.34 μgm^{-3} at JSR. Variations in monthly mean BC mass concentration during summer season in JSR, the monthly averaged concentration of BC mass concentration was noticed around 55.71 μgm^{-3}, 68.29 μgm^{-3}, 63.92 μgm^{-3} and 57.45 μgm^{-3} in February 2025, March 2025, April 2025 and May 2025 respectively. The high value of BC concentrations in JSR was found due to the presence of a nearby industrial area i.e., AIDA (Adityapur Industrial Development Authority). However, in winter season, the average BC concentrations in KGP is 65.58 μgm^{-3}. Monthly averaged concentration of BC mass concentration in Winter Season was noticed around 67.07 μgm^{-3}, 66.68 μgm^{-3}, 62.74 μgm^{-3} and 63.84 μgm^{-3} in October 2024, November 2024, December 2024 and January 2025 respectively as shown in Table 2 and Fig 2. BC mass concentration in KGP, the monthly averaged concentration of BC mass concentration in Summer Season was noticed around 50.42 μgm^{-3}, 49.10 μgm^{-3}, 52.56 μgm^{-3} and 48.70 μgm^{-3} in February 2025, March 2025, April 2025 and May 2025 respectively.

In winter, black carbon (BC) concentrations are typically much higher in urban and industrial regions, and this is largely driven by meteorological conditions—especially the behavior of the mixing layer height and the occurrence of temperature inversions. The mixing layer (or planetary boundary layer) is the lowest part of the atmosphere where pollutants are dispersed vertically. During winter, this layer becomes significantly shallower, often due to reduced solar heating and weaker convection. As a result, emissions from sources such as vehicles, industries, and biomass burning remain confined within a limited vertical space instead of dispersing upward. This leads to the accumulation of BC near the surface, increasing its concentration.



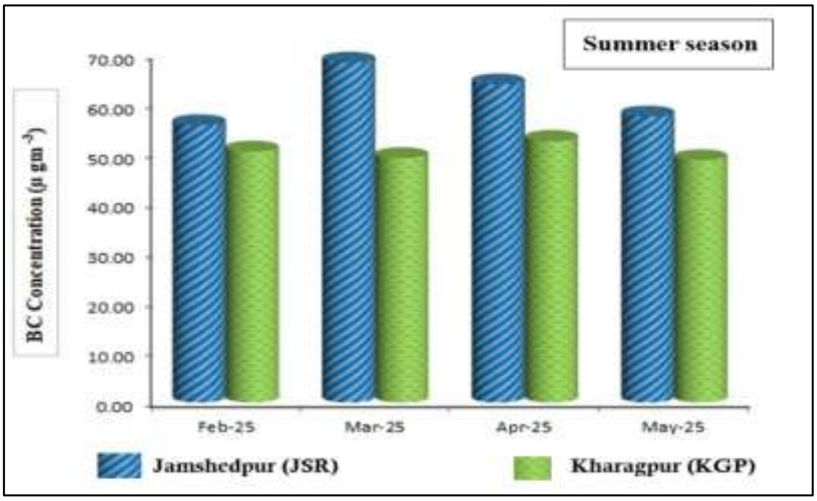


Fig. 2 Comparison of concentration of BC at Jamshedpur and Kharagpur (KGP) during study period.

At the same time, temperature inversion further aggravates the situation. Under normal atmospheric conditions, air temperature decreases with altitude, allowing warm air near the surface to rise and carry pollutants away. However, during a temperature inversion, a layer of warmer air sits above cooler surface air, effectively acting as a lid that prevents vertical mixing. This traps pollutants like black carbon close to the ground, causing them to build up over time. In many eastern Indian industrial cities, winter conditions such as calm winds, high humidity, and frequent inversions create a stable atmospheric environment, which severely limits pollutant dispersion. Consequently, BC concentrations remain elevated for longer periods, increasing both environmental pollution and associated health risks. It was reported that JSR has a higher BC concentration compared to KGP. This is because of AIDA (Adityapur Industrial Development Authority) and dense population in JSR. The elevated levels of BC mass concentration suggest that the atmosphere is mainly affected by pollution from human activities, including the burning of coal, wood, and fossil fuels, among others. The persistent release of BC in Jamshedpur was linked to industrialization and the load of traffic.

Table. 1 Statistical summary of BC mass concentration at Jamshedpur (Industrial Site) during winter and summer.

Winter-24					**Summer-25**				
	Mean	**SD**	**Max**	**Min**		**Mean**	**SD**	**Max**	**Min**
Oct	87.41	25.50	169.41	54.04	**Feb**	55.71	11.47	82.10	36.29
Nov	120.85	37.07	208.66	66.09	**Mar**	68.29	17.43	99.17	29.75
Dec	104.14	30.83	200.76	52.13	**Apr**	63.92	18.68	89.11	24.01
Jan	99.04	35.39	205.06	53.94	**May**	57.45	14.53	87.97	35.62

Table. 2 Statistical summary of BC mass concentration at Kharagpur (Industrial Site) during winter and summer.

Winter-24	**Summer-25**

	Mean	SD	Max	Min		Mean	SD	Max	Min
Oct	67.07	19.31	134.37	36.32	**Feb**	50.42	17.87	76.25	14.46
Nov	66.68	15.48	130.81	41.42	**Mar**	49.09	15.06	68.57	17.07
Dec	62.74	13.94	113.10	33.57	**Apr**	52.56	11.90	78.02	32.09
Jan	63.84	16.87	126.39	29.72	**May**	48.70	14.53	69.00	17.85

3.2 Health risk assessment of black carbon

We calculate the potential hazards that local residents face from exposure to BC emissions during the course of this investigation. Children, who are regularly exposed to BC emission, are thought to be a potential delegate receptor. The daily consumption of reported BC (BC_{REP}) concentration and background BC concentration (BC_{BAK}) level were calculated in order to make an estimate. The 1.25th percentile of the total reported BC set was used to generate the BC_{BAK} [37, 38]. The average BC_{REP} in JSR and KGP was around 81.50 and 57.33 μgm^{-3}, respectively. Similarly, BC_{BAK} was estimated to be around 16.96 and 12.26 μgm^{-3} with the support of BC_{REP}. For the relevant research sites, the starting ΔBC differences between BC_{REP} and BC_{BAK} were 6.34 and 1.73 μgm^{-3}, respectively. At the relevant examination locations, the estimated health risks for CVM and LC-related health concerns were 11.37 and 23.17 NPSC in JSR and 3.11 and 6.32 NPSC in KGP. Due to the high reported BC emission, the observation revealed that the unsurprisingly higher equivalent of passively smoked cigarettes was recorded in JSR.

3.3 Source apportionment of BC at different sampling sites

The percentage distributions of BC_{BB} and BC_{FF}, results of source attribution indicate that the majority of the BC in JSR (57 %) and KGP (53 %) came from BC_{FF} sources due to the extensive commercial exchange of commodities via heavy traffic. There was also a greater contribution of BC_{FF} due to the influence of heavy traffic and more dense industries in the city of JSR.

Due to the combination of stubble burning (BC_{BB}) and city traffic emissions (BC_{FF}), KGP showed rational sources of BC. Around KGP, there are farmlands where people cultivate crops and also established new industries to sustain life. In metropolitan areas, this study showed fractions that are approximately 40–65% at 880 nm, which is similar to the BC_{FF}/BC ratio. Because so many diesel goods vehicles move during the night and early morning, the BC_{FF} fraction is at its highest during these times. The BC_{BB}/BC appears to rise at night. Lower temperatures may lead to a rise in the usage of wood for cooking in rural areas and for fire-borne heating.

3.4 Limitations of the Study

This study is based on single-site rooftop measurements in each city, which may not capture the spatial and vertical variability of black carbon (BC) across different urban environments. The observed concentrations are therefore site-specific and may be influenced by nearby sources rather than representing urban background levels. Consequently, the health risk estimates should be interpreted as indicative of localized exposure rather than city-wide population exposure. Future studies with multiple monitoring locations are needed to improve spatial representativeness.

3.5 Black carbon prevention approach from the environment

In India's metropolitan regions, black carbon, a leading cause of air pollution, represents serious health threats. As the main contributor is the burning of fossil fuels, it is essential to establish efficient control strategies. The implementation of renewable energy sources, including wind and solar power, is resulting in a swift reduction of black carbon emissions. The utilization of public transit and the advocacy for electric vehicle adoption can greatly affect this situation. Diminishing black carbon emissions can be attained by instituting stricter regulations on fuel quality, with a focus on diesel fuel. Enhancing fuel quality can be expedited through the active promotion of cleaner fuels and the provision of financial assistance for their adoption. The reduction of black carbon can be achieved by substituting inefficient combustion systems in residential and commercial settings. Implementing energy-saving practices and encouraging the use of energy-efficient appliances can yield significant benefits. To enhance control measures, stringent emission restrictions for industries and vehicles should be enforced. Regular maintenance and inspections of automobiles can lead to a reduction in black carbon emissions. Advocating for non-motorized mobility, refining public transportation infrastructure, and encouraging compact urban development are significant facets of urban planning. By implementing these measures, the overall dependence on fossil fuels can be significantly diminished. India can efficiently lower black carbon emissions by integrating these approaches, which will improve public health and air quality.

4. CONCLUSION

The averaged mean BC mass concentrations were noticed to be about 102.86 μgm^{-3} at Jamshedpur (JSR) and 65.58 μgm^{-3} at Kharagpur (KGP) in the winter period. The averaged mean BC mass concentrations were noticed to be about 61.34 μgm^{-3} at JSR and 50.19 μgm^{-3} at KGP in the Summer Period. When comparing the JSR site to the KGP site, the highest mass concentration is found there. Because to the large mass concentration of black carbon (BC), the atmosphere is mostly contaminated by human activities such burning coal, wood, and fossil fuels. Due to the significant concentration of black carbon (BC), the atmosphere is predominantly polluted by human activities such as the combustion of coal, wood, and fossil fuels. Due to extensive commercial vehicle movement of goods, source apportionment study also shows that the bulk of BC at JSR (57%), as well as KGP (53%), originate from BCFF sources. The airborne mass movement was also calculated using the 7-day isentropic backward trajectory along with the fire count data. Both local mass burning and air parcel movement contributed to the higher mass concentration. Additionally, the health effects of BC exposure have been assessed for both adults and children. As a result of the elevated reported BC emissions, it was found that JSR had a correspondingly higher equivalent of passively smoked cigarettes. Subsequent studies focusing on the interplay between BC and climate change challenges, such as modified rainfall patterns, temperature fluctuations, and an increased risk of severe weather phenomena, will find this research beneficial, as it will clarify how these interactions could impact BC's conduct, fate, and transport. The findings will enhance the effective communication of BC exposure risks to stakeholders, including communities, policymakers, and industry. Furthermore, collaborative initiatives aimed at bridging the divide between scientific research, policy formulation, and the practical implementation of environmental management and remediation strategies will prove advantageous.

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Author contributions
K.M.Y has done data collections, manuscript preparation, data analysis, review, Typesetting, and T.K.S has done project administration, supervision.

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Data availability
The data will be provided on request.

Declarations
Ethics approval and consent to participate
Not applicable.

Clinical Trial Registration
This study is not a clinical trial involving human participants; therefore, clinical trial registration was not required.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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