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Distribution and Health Risk Assessment of Benzo[a]pyrene in Street Dust of Raniganj in Eastern India

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ABSTRACT

This study investigates the seasonal and spatial distribution of benzo[a]pyrene (BaP) in street dust across Raniganj, revealing significant variations linked to both seasonal shifts and land use types. BaP concentrations in street dust samples ranged from 82.2 ng.g^{-1} to 531.6 ng.g^{-1}, with a mean value of 262.45±75.55 ng.g^{-1}. The highest BaP levels were observed during winter, particularly in heavy traffic, coal mines, and industrial areas, suggesting contributions from industrial activities and vehicular emissions, coal chemical production, and gangue accumulation. An analysis by land use type indicated that BaP levels were highest in busy traffic areas, coal mine areas, and industrial areas, with traffic-congested sites showing the highest average concentration (328.29 ng.g^{-1}). Seasonal analysis showed that winter BaP concentrations were the highest on average (336.28±93.43 ng.g^{-1}), followed by monsoon and summer. These seasonal differences may be due to winter-specific factors, such as increased vehicular traffic, indoor heating, and atmospheric stability. In all five sampling locations, the hazard index (HI) values were moderate for both adults and children. Adults had an average overall cancer risk value of 2.89E-03, whereas children had an average of 2.61E-03, indicating that both age groups are at high risk. Samples collected from various land use types revealed a distinct difference in mean total BaP levels, as well as total cancer risk levels, with the following order observed: busy traffic area > coal mine area > industrial area > commercial area > residential area. The findings underscore the impact of anthropogenic activities and seasonal changes on BaP levels, emphasizing the need for targeted pollution management strategies in heavy-traffic and industrial regions, along with coal mining regions in Raniganj.

INTRODUCTION

Benzo(a)pyrene (BaP) is a polycyclic aromatic hydrocarbon (PAH) that has extensive biological as well as environmental significance. It is a high-molecular-weight PAH consisting of five fused benzene rings. BaP is highly stable, nonvolatile, and non-biodegradable, making it a persistent environmental pollutant (Rajput et al. 2024, Kislay et al. 2024, Ma et al. 2022). It is highly recognized for its potent carcinogenic and mutagenic properties. Owing to its high toxicity and prevalence in nature, BaP is often used as a marker of PAH pollution in the environment (Souza et al. 2016). Similar to other PAHs, BaP is emitted into the environment via several anthropogenic sources. It is mainly a byproduct of incomplete combustion of organic materials like burning of fossil fuels, vehicular emissions, domestic heating, burning of wood, various industrial activities, tobacco smoking and grilling/charring of food materials (Bukowska et al. 2022, Hellén et al. 2017, Srogi 2007). A small amount of BaP is also released into the

environment via natural processes, such as forest fires and volcanic eruptions. Once released into the environment, BaP tends to adhere to the atmospheric particulate matter as well as to the sediments of aquatic systems, where it can persist for a long time because of its hydrophobic nature and chemical stability (Maletic et al. 2019, Hussain et al. 2018). Atmospheric dry and wet deposition and the runoff process distribute BaP in soil, street dust, and water bodies, from where it enters food chains and starts bioaccumulating in the bodies of organisms (Saravanakumar et al. 2022). Due to its greater surface area and smaller particle size, street dust acts as a good harbor for BaP accumulation (Franco et al. 2017). It has a crucial direct connection to humans in day-to-day life, thus making it an important environmental matrix to investigate BaP concentration.

Ingestion, inhalation, and skin contact are the three main exposure routes through which BaP can enter the human body (Ali et al. 2021). A significant source of BaP exposure in humans can be food, particularly if it is burned or smoked. Through intricate biotransformation processes, cytochrome P450 enzymes found in the liver and other tissues gradually activate BaP into highly reactive compounds (Hand 2001). Among the several metabolites formed, BaP-7,8-diol-9,10-epoxide is a potent mutagen that can form a covalent link with DNA and produce adducts that disrupt regular cellular functions, such as replication, and induce mutations (Koh & Pan 2024). BaP is a significant material in cancer research because some of these DNA adducts have been linked to the early stages of cancer formation, specifically in the lung, liver, skin, and bladder (Zhao et al. 2024, Das & Ravi 2022). According to various epidemiological studies, BaP exposure can cause several other medical issues, such as cardiovascular diseases and developmental problems in children (Alias et al. 2022). It can impair immunity, making it more difficult for the body to eliminate several illnesses. BaP can adversely affect the female reproductive system, leading to lower birth weights, delayed child development, and decreased fertility (Jorge et al. 2021). BaP may also cause chromosomal defects, leading to genetic instability.

Several researchers throughout the globe have thoroughly researched PAHs on the street and their related health effects (Dytlow et al. 2025, Adeniran et al. 2025, Li et al. 2025). This research indicates increasing concerns over the occurrence and sources of PAHs in street dust. Similar to global trends, third-world nations such as India are becoming increasingly concerned about PAH concentrations in street dust (Nayak et al. 2023). PAHs in street dust have been found to contribute to severe human health risks through their carcinogenic, mutagenic, and toxic nature. Among these compounds, BaP is the most active and dangerous PAH and is frequently used as an indicator for evaluating the

environmental toxicity of the overall PAH mixture (Kumar et al. 2013). Owing to the high impact of BaP on human health, the International Agency for Research on Cancer (IARC) has classified it as a Group 1 carcinogen. BaP is also regulated under Section 112(b) of the 1990 Clean Air Act Amendments, which is classified as a hazardous air pollutant (HAP) within the category of substances known as polycyclic organic matter, as 7-PAH (USEPA 2006). Several regulatory bodies worldwide have set limitations and guidelines for BaP exposure because of its ability to induce potential health impacts. According to the Canadian Council of Ministers of the Environment, BaP levels in residential, industrial, and agricultural soil are allowed to be between 0.015 to 0.7 $mg.kg^{-1}$, 0.7 to 2.1 $mg.kg^{-1}$ and 0.1 $mg.kg^{-1}$, respectively (CCME 2010). In India, the proposed ambient air limit for BaP is 1.0 $ng.m^{-3}$ (Gazette of India 2009). However, the situation concerning BaP remains challenging despite restrictions and regulations, particularly in regions where high levels of industrial and vehicular emissions are not effectively managed. The use of various advanced technologies and thorough monitoring of BaP levels in all environmental matrices is crucial for mitigating its long-term effects on the environment (Sushkova et al. 2016).

According to the Ministry of Coal, Government of India, 64 coalfields are currently in operation in India, with an estimated reserve of approximately 378.21 billion tonnes (National Coal Inventory 2023). Of these, 33.93 billion tonnes of the country's total coal resources belong to the state of West Bengal. Raniganj Coalfield, on the western bank of the Damodar River, is among the oldest and most historically notable coalfields in India (Mondal et al. 2018). Coal mining operations, such as extraction methods, disposal of mining waste materials, and coal processing residues, have been identified as the principal sources of PAHs in coal mine areas (Chen et al. 2019, Qian et al. 2022). Masto et al. (2015) analyzed the concentration of PAHs in the surface soils of underground mines in this region. Unfortunately, there have been no follow-up studies on PAHs in other environmental media, especially street dust. As a critical sink for PAHs and a potential health hazard due to exposure via numerous pathways, it is crucial to examine the levels of various PAH types in this matrix. Moreover, few studies have been conducted in India regarding BaP levels in ambient air (Garg et al. 2022), and no research has been conducted on the level of BaP in street dust. This is an important research gap considering BaP's toxicity and carcinogenic potential. With these research gaps taken into account, this study aims to (a) conduct a bibliometric analysis to identify research trends in India within the existing literature, (b) assess BaP concentrations by comparing seasonal variations (summer, monsoon, and winter) and spatial differences across

various land-use types, including residential, commercial, industrial, coal mining, and busy traffic areas, (c) assess the carcinogenic health risk and hazard index (HI) for two different age groups (adults and children), and (d) conduct a comparative analysis between the present findings and previously reported studies across the globe.

MATERIALS AND METHODS

Methodology: Bibliometric Analysis

The research data were collected on the 25th of February 2025 from the Web of Science. The database used was Web of Science Core Collection, and a search was done using the Advanced Search Query Builder (Laha et al. 2024, Pal et al. 2025, Gupta et al. 2024b). The search query term was as follows: TS=(PAHs) OR TS=(polycyclic aromatic hydrocarbons) OR TS=(BaP) OR TS=(Benzo[a]pyrene) AND TS=(road dust) OR TS=(street dust) AND TS=(India). Here, TS refers to the topic field. A total of 117 publications were available up to the date of the search. The authors used VOS viewer – a data analysis and visualization software first developed at the Centre for Science and Technology Studies, Leiden University, The Netherlands (Gupta et al. 2024b, Koley et al. 2023, Van Eck et al. 2010). In particular, this was a method of analyzing keyword co-occurrence networks, following the search trends in the recent literature, and pinpointing the core clusters within the literature.

Bibliometric analysis was performed using VOSviewer software to create a co-occurrence map using bibliographic data scraped from the Web of Science database advanced search. The co-occurrence relationships between the various keywords were emphasized, with all keywords selected as a unit of analysis. A full counting method was used, that is, every occurrence of a keyword was counted equally (Gupta et al. 2024a, Koley et al. 2024). To maintain accuracy and comprehensibility, the empowerment or feeding of the system was decided to be stopped at the fourth share, that is, where a keyword has at least three counts. Of the 690 keywords and co-occurrence relationships under study, 124 keywords maintained this threshold, and 66 words were eventually chosen for visualization and analysis.

Study Area

The study was conducted in the Raniganj region, situated in the Asansol-Durgapur industrial belt within the Paschim Bardhhaman district in the state of West Bengal, India. Mining operations in the Raniganj Coalfield began in 1774AD and continue extensively today. The coalfield spans areas in West Bengal and Jharkhand. Within West Bengal, it primarily covers parts of the Bardhaman district, with adjacent regions extending into the Birbhum, Bankura, and Purulia districts. In Jharkhand, portions of the coalfield are situated in the districts of Dhanbad and Santal Pargana (Manna & Maiti 2018). Coal mining, steel production, sponge iron production, and other industries contribute to diverse environmental challenges that heavily influence the region's economic landscape. Fifteen distinct sampling sites were chosen from five distinct land use patterns: residential, commercial, industrial, coal mine, and busy traffic areas (Fig. 1).

Street dust was collected during three different seasons (summer, monsoon, and winter) during the day on weekdays. Three sampling locations separated by one meter were chosen for each land use. Approximately 500 g of samples
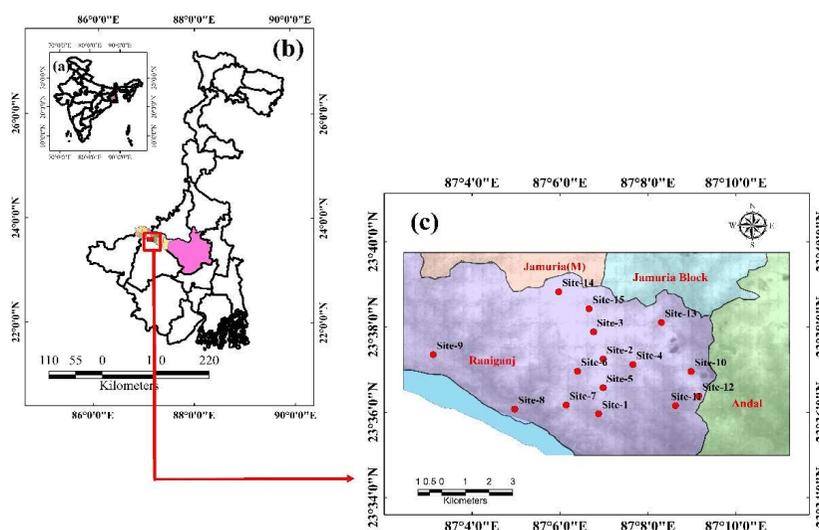

Fig. 1: Location map of the study area.

were collected from each sampling location and then combined to create a single composite sample. Three composite samples were collected from each land use type. To prevent the resuspension of extremely fine particles during the sampling process, samples were collected using a brush and swept directly into plastic bags (Gope et al. 2018). The collected samples were then cleared of extraneous items such as cigarette butts, tiny gravel, discarded plastics, metal scraps, and demolished building debris. The samples were sieved to a particle size of less than 63 µm (Gope et al. 2020). They were then kept in zip-locked plastic bags in a refrigerator at a temperature of less than 4°C until analysis.

Extraction and Analysis of PAHs

For the analysis of PAHs, samples were extracted in a Soxhlet apparatus using a 10:1 toluene: methanol mixture, as per the USEPA method 3540C (USEPA 1996a). Approximately 10 g of the sample was placed in an extraction thimble and placed in a Soxhlet apparatus, and 300 mL of the extraction solvent was placed in a 500 mL round-bottom flask containing two or three clear boiling chips. The flask was then attached to the extractor, and samples were extracted for 16-12 hours at 4-6 cycles/hour. After extraction, the samples were cooled, reduced to 2 mL using a rotary evaporator, filtered, and cleaned using silica gel column chromatography according to the USEPA method 3630C (USEPA 1996b).

After cleanup, the extracts were concentrated to 1 mL using a gentle flow of nitrogen. GC-FID (Agilent 8890-GC) analysis was performed to determine the PAHs in the extracts according to the USEPA method 610 (Hishamuddin et al. 2023). For the GC system, the initial oven temperature was 140°C (held for 3 min), then raised from 140°C to 250°C at 6°C.min^{-1} (held for 6 min), then further to 300°C at 5°C.min.$^{-1}$, and finally held for 5 min. With a total flow of 24 mL.min^{-1} and a pressure of 7.0856 psi, the injector was set to 320°C in the split mode with a split ratio of 20:1. The septum purge flow was 3 mL.min^{-1}. The FID heater was operated at 320°C and 30 mL.min^{-1} of hydrogen gas flow. The makeup flow (N$_2$) was 28.8 mL.min^{-1}. A typical HP-5MS capillary column (30 m length, 320 µm diameter, and 0.25 µm film) from Agilent was utilized. The injection volume was set to 1µL with a column flow of 1 mL.min^{-1}, and the USEPA-recommended 16 PAHs were analyzed.

Health Risk Assessment

A risk assessment model was developed by the United States Environmental Protection Agency (USEPA 2002, USEPA 1989) to ascertain the risk to both adults and children. In

this model, humans are exposed to contaminated road dust particles through three major pathways: (1) ingestion via oral intake, (2) dermal absorption via skin contact, and (3) inhalation via the respiratory tract. The chronic exposure risk for benzo [a]pyrene (BaP) was determined from the average daily dose (ADD) calculated for these various exposure pathways.

$$ADD_{Ingestion} = \frac{CS \times IR_{Ingestion} \times EF \times ED}{BW \times AT \times 10^6} \quad \text{...(1)}$$

$$ADD_{Dermal} = \frac{CS \times SA \times AF \times ABS \times EF \times ED}{BW \times AT \times 10^6} \quad \text{...(2)}$$

$$ADD_{Inhalation} = \frac{CS \times IR_{Inhalation} \times EF \times ED}{BW \times AT \times PEF} \quad \text{...(3)}$$

Where CS is the BaP concentration in street dust (ng.g^{-1}), and BW is the body weight (kg). AT is the average lifespan (days). EF is the exposure frequency (day.year^{-1}). ED is the exposure duration (in years). IR$_{Inhalation}$ is the inhalation rate (m^3.day^{-1}). IR$_{Ingestion}$ is the soil intake rate (mg.day^{-1}). SA is the dermal surface exposure (cm^2). AF is the dermal adherence factor (mg.cm^{-2}). ABS is the dermal adsorption fraction of the chemical. PEF is the particle emission factor (m^3.kg^{-1}). 10^6 is the conversion factor. The values of the variables are listed in Supplementary Table 1 for both adults and children.

The level of danger for BaP was determined by the ratio of ADD (for three different exposure routes) to the reference dose (RfD).

$$HQ = \frac{ADD}{RfD} \quad \text{...(4)}$$

The reference dose (RfD) is defined as the estimated daily human exposure to an agent that is unlikely to cause adverse health effects in humans. It is based on the best available science and is intended to protect both present and future generations from the development of any potential pathological changes or diseases (Kosheleva et al. 2023). Reference doses have been estimated for BaP for the three exposure routes. For ingestion and dermal exposure, it is 3×10^{-4} mg.kg^{-1} (USEPA 2002), and for inhalation, it is 2×10^{-6} mg.kg^{-1} (USEPA 1989).

$$HI = \sum HQ \quad \text{...(5)}$$

The HI indicates the extent to which combined health hazards are presented by several exposure pathways through which hazardous dust particles can enter the human body. Four categories of negligible (<0.1), low (0.1-1), moderate (1-10), and high (>10) health risk levels are derived from the overall HI (Kosheleva et al. 2023, USEP 2002).

To assess the age-specific potential cancer risks (children and adults) of human exposure to BaP, the incremental lifetime cancer risk (ILCR) model is used (USEPA 1989, USEPA 2002)

$$ILCRs_{(Ingestion, inhalation, dermal)} = ADD \times CSF \times \sqrt[3]{\frac{BW}{70}} \quad \text{...(6)}$$

Where CSF is the cancer slope factor in mg.kg^{-1}. day^{-1} for the three different exposure routes.

Total Crcinogenic Risk=
$$ILCR_{Ingestion} + ILCR_{Inhalation} + ILCR_{Dermal} \quad \text{...(7)}$$

Generally, the acceptable risk range for total carcinogens is set to 10^{-6} to 10^{-4} by the USEPA (USEPA 2001), and risks below 10^{-6} do not require any additional action, while risks above 10^{-4} are considered to be of concern and require further action to reduce the exposure and resulting risk (USEPA 2008).

Preparation of the Spatial Pattern of BaP

Inverse Distance Weighting (IDW) is a spatial interpolation technique that is prepared in a GIS (Geographical Information System (GIS) environment to plot the missing value in a region using known data points (Lu 2008). In this study, spatial interpolation was a beneficial method not only to identify the distribution of BaP in dust or carcinogenic risk distribution, but also to correlate with other components. The major principle of IDW is that the prediction capacity of a known value decreases with increasing distance (Moussa & Abboud 2024, Achilleos 2008). The estimated value has been calculated with the help of the following formula.

$$\bar{Z_s} = \frac{\sum_{i=1}^{n} w_i Z_i}{\sum_{i=1}^{n} w_i} \quad \text{...(8)}$$

Where, Z_s = Estimated value of unknown location, Z_i = Known neighboring value, W_i = Weight assigned to each known point, n = Number of neighboring points.

The weight is computed as

$$* \qquad W_i = \frac{1}{d_i^p} \quad \text{...(9)}$$

Where, d_i = distance between the known and unknown point, p = Power value regulating the effect of distance (typically set between 1 and 3). IDW is a widely used interpolation method in GIS applications due to its simplicity and effectiveness. But before that, we must make a strong data set to show this spatial variability.

IDW is a popular method of interpolation. This helps to determine the spatial variability of components in a more or less accurate manner. However, there are several drawbacks to this method; for example, it assumes that the spatial relationship is not the same in all directions, so it does not address directional trends (Barbulescu & Saliba 2024). Moreover, the precision of the IDW depends on the density and distribution of the sample points. If the points are more random, there will be an error in that area (Achilleos 2011). IDW offers no indication of a forecast as other methods do (Achilleos 2008, Benmoshe 2025). IDW ignores topographic and physical barriers that may affect spatial variation, as it only depends on mathematical distance (Lu 2008). But it may be a very useful tool for air-water quality analysis, as we have done in this research (Jumaah et al. 2019, Yadav & Ganguly 2024)

RESULTS AND DISCUSSION

Current Scenario of BaP in Street Dust: A Bibliometric

A bibliometric overview of research on polycyclic aromatic hydrocarbons (PAHs) in Indian street dust identified seven distinct thematic clusters (Fig. 2). Cluster 1 (Red) consists of 27 keywords such as "PAHs", "polyaromatic hydrocarbon", "source apportionment", "PM$_{10}$", "PM$_{2.5}$", "black carbon", "emission", and "urban site" This group is basically concerned with territories which link the PAHs with the particulate matter (PM$_{10}$ and PM$_{2.5}$) in urban locations. Major sources mainly are emissions from vehicle exhaust gases, such as industrial activity, while on the other side, there can be emissions due to biomass burning and burning of fossils and fuels. In the name of source apportionment, efforts have been made to determine the main sources of PAHs in the environment. Soot is indicated by "Black carbon," meaning that this research was conducted on them through which PAHs will be available in indoor air quality. The term "urban site" is used to signify that PAH contamination is ubiquitous in highly populated areas, thereby indicating that traffic and industrial emissions are high. This cluster focused on determining the presence of PAHs in street dust, soil, and sediments and their effects on human health and ecological systems. PAHs accumulate in surface sediments and road dust, and exposure through inhalation, ingestion, and dermal contact is potentially risky.

Cluster 2 (Green) includes 24 items, i.e., "street dust", "surface dust", "indoor dust", "surface sediments", "urban street dust", "soil", "road dust", "health risk assessment", "ecological risk" and "human exposure". This cluster has focused on determining how PAHs are present in street dust, soil, and sediments and their effects on human health and ecological systems. PAHs accumulate in the surface sediments and road dust, in which exposure through inhalation, ingestion, and dermal contact is potentially risky. "Indoor dust" suggests the possibility that PAHs move into homes from outside and thus induce a higher risk for longer exposure. In this cluster, studies assess ecological risk assessments and levels of human exposure to understand the long-term effects of PAH contamination. Cluster 3 (Blue):

21 items comprise "street dust", "contaminated soil", "urban soil", "sediments", and toxic metals such as "Ni, Pb, Cu, and Cd". The presence of heavy metals like Nickel (Ni), Lead (Pb), Copper (Cu), and Cadmium (Cd) is indicative of the fact that PAH pollution is generally accompanied by metal pollution. The sources for these metals comprise industrial discharge, vehicular emissions, and urban runoff. Heavy metal pollution thus poses a serious threat to environmental and human health. The correlation between PAHs and heavy metals in urban soils gives credence to the possibility of synergistic toxicity, which aggravates the pollution. The studies in this cluster aim to study the levels of contamination in the soil, source term, and remediation measures.

Cluster 4 (Yellow): 17 items include "city", "impacts", "pollution indices", "accumulation", "urban soil", "roadside" and "Kolkata". The studies of this cluster examine the urban pollution burden of some leading Indian cities with a pronounced focus on Kolkata. The use of terms like "pollution indices" and "accumulation" indicates that quantitative evaluations of PAH pollution rely on various indices to determine the severity of contamination. The term "roadside" is indicative of traffic emissions as a major source of PAHs. Referral to "Kolkata" is indicative that studies here are focused on studying the sources and the level of various kinds of pollution in the West Bengal capital, which is an industrialized and densely populated area. Cluster 5 (Purple)-13 words include "diagnostic ratio", "health risk", "agricultural soil", "river" and "surface soil". The term "diagnostic ratio" doesn't reveal much about the type of research conducted in this cluster except that fingerprinting

techniques are used to differentiate between two sources of PAHs, i.e., pyrogenic (combustion) and petrogenic (oil). The mention of "agricultural soil" and "river" in this cluster indicates that PAHs are transported out of urban centres into agroecosystems and river ecosystems and thus potentially threaten food chains through bioaccumulation and pollution of these waterways. The "health risk" in this cluster refers to PAHs exposure via contaminated soil and water in places where agricultural use is widely prevalent. Cluster 6 (Sky Blue) contains 12 items, including "carcinogenic risk", "hazard index", "source profile" and "hazard quotient". Research in this cluster mainly relates to the risk assessment methods used for evaluating PAHs-related cancer and non-cancer health risks. The mention of "children" is indicative of the concerns regarding the vulnerable population, because the children are at great risk of PAHs exposure, as they tend to put their hands in their mouths and are also exposed to contaminated dust for prolonged periods. The terms "hazard index" and "hazard quotient" point to quantitative methods of assessing levels of toxicity to define safe exposure limits. This cluster relies heavily on health interventions to derive public health policy concerning PAH risk. The last cluster (Cluster 7, Orange), containing 7 items, includes "Delhi", "West Bengal", "soils", "heavy metals" and "source". The series of regional studies on PAHs clustered here focuses on places with peak industrial and urban activities: Delhi and West Bengal. As India's capital, Delhi is notorious for immense pollution from vehicle emissions, industrial sources, and biomass burning, which has given rise to severe air quality problems. On the other hand, West Bengal has

Fig. 2: Co-occurrence network.

numerous industrial bases with a huge population density that suffers heavy soil and air contamination from both PAHs and heavy metals. The keyword "source" indicates the research being done to identify the major sources responsible for PAHs pollution in the location selected.

Seasonal Variation of BaP

The total BaP content in the street dust of Raniganj ranged from 82.2 ng.g^{-1} to 531.6 ng.g^{-1} with a mean value of 262.45±75.55 ng.g^{-1}. A significant variation in BaP level was observed among different sampling sites across the study area in three different seasons (Fig. 3a, 3b, 3c). During winter highest BaP concentration was found at site 9 (531.60 ng.g^{-1}), followed by site 13 (430.00 ng.g^{-1}), site 14 (398.52 ng.g^{-1}) and site 7 (395.00 ng.g^{-1}). In summer, site 9 (290.63 ng.g^{-1}), site 11 (278.43 ng.g^{-1}), site 13 (273.80 ng.g^{-1}), and site 12 (263.25 ng.g^{-1}) showed the highest level of BaP among all the sites. While in monsoon, a maximum level of BaP was detected in site 9 (476.70 ng.g^{-1}), followed by site 13 (351.67 ng.g^{-1}), site 15 (325.90 ng.g^{-1}) and site 14 (321.70 ng.g^{-1}). In winter seasons, elevated levels of BaP in their respective sites might be due to various industrial activities (steel, sponge iron, cement, food processing) as well as vehicular exhaust emissions because of high traffic loads near some sites (Kosheleva et al. 2023). But in the monsoon, higher BaP levels in those sites can

be attributed to an increase in the number of transportation activities and runoff of contaminants, along with wind deposition from surrounding polluted areas. The lowest BaP concentration was found at site 2 during winter and monsoon, whereas at site 1 in summer. The mean BaP concentration of this study area was compared with some other studies across the world. The mean BaP value was similar to the values observed from Moscow, Russia (Kosheleva et al. 2023), Kuala Lumpur, Malaysia (Hishamuddin et al. 2023), Karaj, Iran (Qishlaqi & Beiramali 2019), Trinidad, Caribbean (Mohammed et al. 2018) and Xuzhou, China (Wang 2018). The mean concentration of BaP, on the other side, was much lower than the values reported from Shenzhen, China (3089.07 ng.g^{-1}) (Ning et al. 2023), Ibadan, Nigeria (2528 ng.g^{-1}) (Yusuf et al. 2022), Jeddah, Saudi Arabia (1513.51 ng.g^{-1}) (Shabbaj et al. 2018), Tokyo, Japan (2100 ng.g^{-1}) (Khanal et al. 2018) and Ulsan, Korea (6310 ng.g^{-1}) (Lee and Dong 2010) whereas much higher than that of found in Daejeon city, South Korea (28.59 ng.g^{-1}) (Lee et al. 2023), Tyumen city, Russia (26.07 ng.g^{-1}) (Konstantinova et al. 2022), Yazd, Iran (26.10 ng.g^{-1}) (Nematollahi et al. 2021), Myanmar (45.5 ng.g^{-1}) (Mon et al. 2020) and Buenos Aires, Argentina (26.4 ng.g^{-1}) (Cappelletti et al. 2019). These findings suggest that the levels of BaP in street dust differ globally. These discrepancies may be related to changes in the volume and
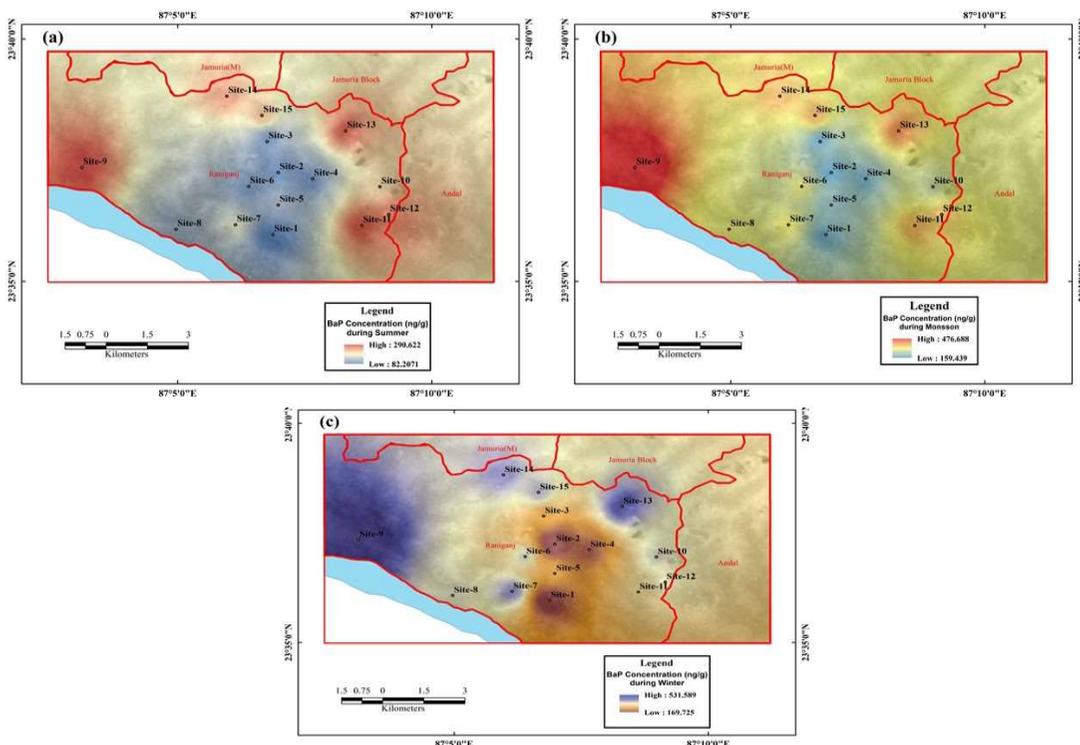

Fig. 3: Seasonal variation in BaP levels across 15 street dust samples (n= 15) from Raniganj during (a) summer, (b) monsoon, and (c) winter.

intensity of human activity, traffic loads, vehicular emissions, various technologies used, numbers of industrial activities, cooking patterns, the frequency of city street cleaning, and regional weather patterns like temperature differences, wind speeds and rainfalls that degrade, disperse and eliminate PAHs from street dust (Shabbaj et al. 2018, Hussain et al. 2015, Soltani et al. 2015).

Spatial Variation of BaP

Street dust collected from different land use types in Raniganj indicated an apparent disparity in mean total BaP levels (Fig. 4a), which was found to be in the order of busy traffic area > coal mine area > industrial area > commercial area > residential area. The highest value of BaP in busy traffic areas (328.29 ng.g^{-1}) followed by coal mine areas (323.68 ng.g^{-1}) implies the effects of high traffic congestion, vehicular emissions, coal chemical production, transportation of coal, leaching/weathering of coal beds and gangue accumulation (Gope et al. 2020, Masto et al. 2019). The lowest BaP concentrations were observed in residential areas (158.39 ng.g^{-1}), which might be due to its land use type, lower traffic loads, comparatively low vehicular emissions, minimal anthropogenic activities and absence of other non-

point sources. The percentage contribution of mean total BaP levels of the residential, commercial, coal mine, industrial and busy traffic areas over the whole study area was 12.07%, 15.86%, 24.87%, 22.38% and 25.02%, respectively (Fig. 4b).

The BaP concentration in street dust of Raniganj varied significantly between the three seasons (Table 1). The mean BaP concentrations during the winter ranged from 214.23 ng.g^{-1} to 426.67 ng.g^{-1} with a mean of 336.28± 93.43 ng.g^{-1}, and during the monsoon varied from 167.44 to 344.37 ng.g^{-1} with a mean of 269.17±87.83 ng.g^{-1}, and ranged between 93.50 ng.g^{-1} and 249.90 ng.g^{-1} with a mean of 181.90±76.46 ng.g^{-1} during the summer. An increase in BaP level was observed during winter and monsoon in comparison to summer. Changes in weather patterns and existing human activity may be the cause of the varying seasonal concentrations throughout the year. Because of the thin layer of street dust and the potential for absorption and reflection of sunlight over a prolonged period by the street asphalt, along with very high temperatures, BaP is subject to photo-degradation and volatilization during summer.

Furthermore, since BaP is typically adsorbed onto very small particles, the swiftly moving vehicles on the street lift the fine dirt particles and aid in BaP dispersion by strong
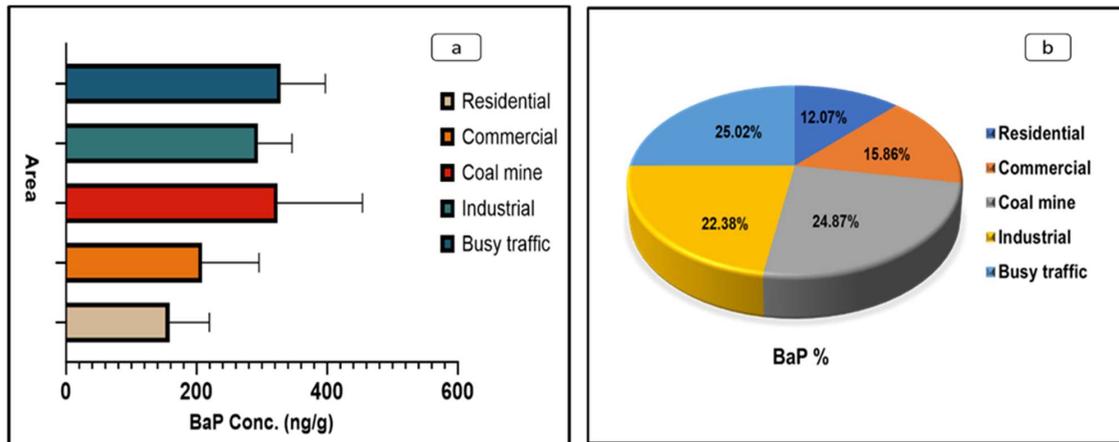

Fig. 4a: Spatial differences in BaP concentrations across various land-use types based on street dust samples (n=15) from Raniganj. Fig. 4b: BaP level percentage across various land-use types.

Table 1: Total and seasonal area-wise BaP content in street dust of Raniganj.

Sample matrix	Concentration of BaP [ng.g^{-1}]	Area	Season variation of BaP [ng.g^{-1}]		
			Winter	Monsoon	Summer
Street dust (<63 μm)	262.45±75.55	Residential	214.23±60.20	167.44±7.96	93.50±9.95
		Commercial	293.97±63.72	212.77±53.79	117.83±14.95
		Coal mine	426.693.22±7	344.37±114.77	200.01±80.91
		Industrial	344.63±13.31	288.20±46.43	248.26±39.84
		Busy traffic	401.89±26.58	333.09±16.23	249.90±23.65
		Mean total	336.293.43±8	269.17±87.83	181.90±76.46

wind, which may lead to low levels on the street side in the summer as compared to winter and monsoon (Gope et al. 2018). Primarily, an increase in vehicular traffic, indoor and outdoor heating and cooking activities during winter elevate the BaP level in winter (Manoli et al. 2016, Liu et al. 2007). Other factors such as various climatic conditions like lower temperature, high atmospheric stability, lower atmospheric mixing height, low volatilization, shorter daylight, thermal inversion, reduced vertical dispersion, low photochemical activity and increased particle adherence, could be the reason for higher BaP levels in winter in comparison to the other two seasons (Gope et al. 2020, Khillare et al. 2014).

While considering five land-use types, distinct variations in BaP levels were detected in three different seasons (Table 1). The highest BaP value was observed in the coal mine area for winter and monsoon, while in summer, it was for busy traffic areas. On the other side, the lowest BaP value was found in a residential area for all three seasons.

Risk Assessment

The assessment of adverse health effects was established for the urban population using BaP data in terms of chronic ADD from contaminated street dust. Ingestion and dermal ADDs were noted to be similar between adults and children, while values for inhalation were markedly lower. For ingestion, the estimated amounts were in the range of 2.72E-04 to 5.63E-04 and 4.53E-04 to 9.38E-04 for adults and children, respectively. Inhalation values ranged between 3.99E-08 and 8.28E-08 for adults, and for children, values were in the range of 1.66E-08 to 3.45E-08. Values of dermal absorption were recorded in the range of 1.41E-04 to 2.92E-04 and 1.65E-04 to 3.41E-04 for children. Between age groups, for ingestion and dermal exposure, children had higher ADD values than adults, whereas adults had higher values for inhalation. The HI values (Table 2) indicate moderate levels for both adults and children across the five sampling areas, with HI values varying between 1 and 10. However, it was observed that children had higher HI values than adults. Among the study areas, the highest HI values were observed for areas with high traffic density, followed by areas near coal mining activities.

According to the calculated cancer risk (Table 2), the risk for adults from ingestion and skin contact was between E-03 and E-02, which is the same as the risk for children. The risk of inhalation in this case was between E-08 and E-07, which was 10^5 times lower than the risk of ingesting and skin contact. Thus, compared to the other two exposure pathways, inhalation of dust particles from the streets was insignificant (Gope et al. 2018). This finding is consistent and similar to previously reported studies by other researchers (Ning et al. 2023, Kosheleva et al. 2023, Gope et al. 2020, Masto et al. 2019). The reason behind the higher value of ILCR for ingestion and dermal compared to Inhalation might be due to the respiratory system's innate defences that are more effective at screening out particles before they enter the bloodstream, while ingested and absorbed substances have a more direct route to internal organs (Sousa et al. 2022, Ramesh et al. 2004). The levels of cancer risk associated with ingestion and dermal contact were within the same order of magnitude, suggesting that these exposure routes significantly increased the risk of cancer in both adults and children. Nonetheless, children were far more at risk of direct consumption than adults because they were more susceptible to hand-to-mouth activity and had lower body weight, which makes it easy for them to consume contaminated dust (Gong et al. 2022).

On the other side, dermal contact induced a comparatively higher risk in adults than in children. In the present study, all 5 different areas showed significantly higher total carcinogenic risk for both adults and children, as the values exceeded ILCR$> 10^{-4}$. In the case of seasonal variation, winter has the highest carcinogenic risk for all five areas, followed by the monsoon and the summer. Sites 7, 8, and 9 had greater values throughout the winter (Fig. 5a, 5b) and monsoon seasons for both adults and children (Fig. 5c, 5d), while sites 13, 14, and 15 had the highest values during the summer (Fig. 5e, 5f). The carcinogenic value increased in the order of residential area < commercial area < industrial area < coal mine area < busy traffic area. Although the residential area showed a lower cancer risk than the other four areas, it fell under the high carcinogenic risk category. The mean total cancer risk values obtained for adults and children were 2.89E-03 and

Table 2: HI and results for ingestion, inhalation, dermal and total cancer risk for children and adults in the street dust of Raniganj.

| Area	Child ingestion	Child inhalation	Child dermal	Total cancer risk	Adult ingestion	Adult inhalation	Adult dermal	Total cancer risk	Child HI	Adult HI
Residential	2.10E-03	4.07E-08	2.62E-03	4.72E-03	1.88E-03	1.46E-07	3.34E-03	5.23E-03	2.07	1.39
Commercial	2.76E-03	5.35E-08	3.44E-03	6.20E-03	2.47E-03	1.92E-07	4.40E-03	6.87E-03	2.72	1.83
Coal mine	4.29E-03	8.32E-08	5.35E-03	9.64E-03	3.85E-03	2.98E-07	6.84E-03	1.07E-02	4.22	2.85
Industrial	3.90E-03	7.55E-08	4.86E-03	8.75E-03	3.49E-03	2.71E-07	6.20E-03	9.69E-03	3.83	2.59
Busy traffic	4.35E-03	8.44E-08	5.43E-03	9.78E-03	3.90E-03	3.03E-07	6.93E-03	1.08E-02	4.28	2.89
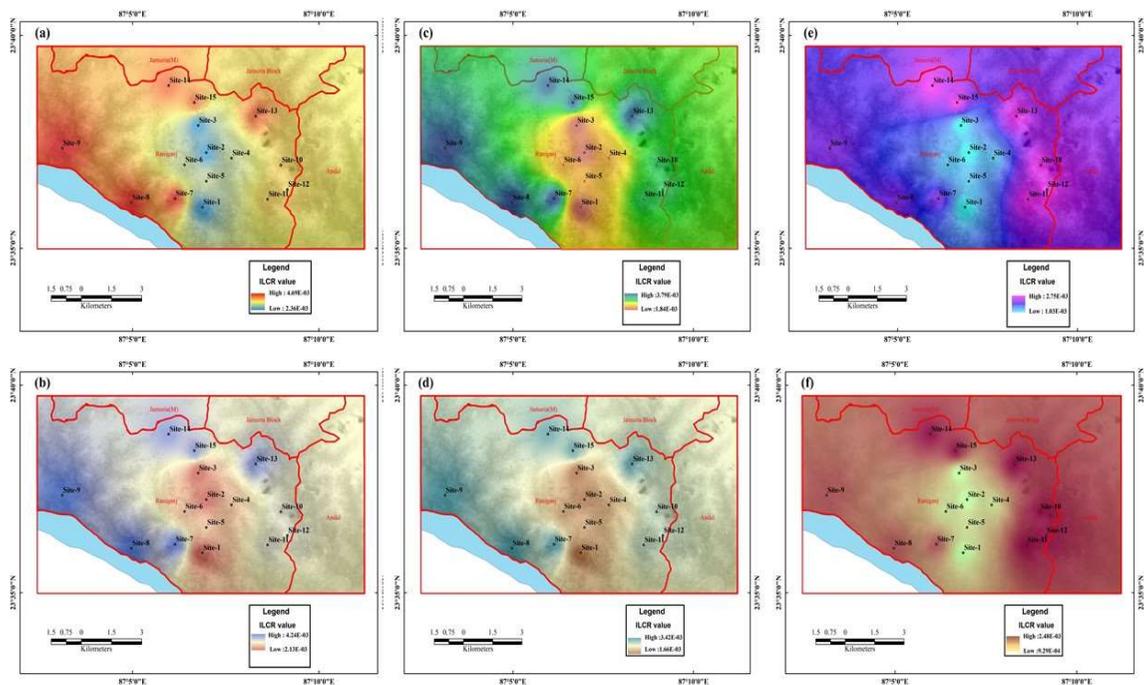
Fig. 5: Seasonal Variation (a: winter-adult, b: winter-child, c: monsoon-adult, d: monsoon-child, e: summer-adult, f: summer-child) in ILCR Levels in street dust (n=15) of Raniganj.

2.61E-03, respectively. Similar cancer risk magnitudes for both adults and children have been observed in recent studies over street dust from Kuala Lumpur, Malaysia (Hishamuddin et al. 2023), Huainan, China (Xu et al. 2022), Lagos, Nigeria (Iwebue et al. 2021), Karaj, Iran (Qishlaqi & Beiramali 2019) and Dresden, Germany (Zhang et al. 2019).

BaP in Street Dust and Associated Cancer Risk Across Different Cities: an Indian and Global Perspective

The concentration of BaP in the street dust and cancer risk of the present study has been compared with the BaP level in the street dust and ILCR value of previously reported studies across India (Table 3, Fig. 6, Fig. 7). In the present study, the BaP concentration was significantly higher than the reported concentrations of street dust in Guwahati (Hussain et al. 2015), New Delhi, and Bangalore (Tue et al. 2014). The BaP levels were 6-, 4.2-, and 5-fold higher than those in Guwahati, New Delhi, and Bangalore, respectively. The cancer risk in these three areas fell under E-04, which is one magnitude lower than the value obtained in the present study. The reported level of BaP and estimated cancer risk in street dust of Raipur (Patel et al. 2015) and Dhanbad (Tarafdar and Sinha 2019, Masto et al. 2019) were comparatively higher than the value obtained in the present study. Two separate studies from Durgapur (Gope et al. 2020) and Asansol (Gope et al. 2018), which are the adjacent towns of Raniganj, are compared for their BaP levels. Among them,

Durgapur showed slightly lower BaP concentrations in street dust as compared to this study. At the same time, for Asansol, the levels were almost similar to the present study signifies the presence of similar kinds of Emission sources. The cancer risk values of Asansol and Durgapur were more or less similar to the value of the present study, which fell under E-03.

Only one study (Nayak et al. 2023) comprising three separate locations, among which street dust from Bhilai and Korba depicted extremely high BaP levels (26 to 27 times) than the level of BaP from Raniganj, while another location, Raipur, showed 7.6 times higher concentration than the present one, which is also relatively high. The ILCR value of these areas was higher than the value of Raniganj, which is E-02. Therefore, the total cancer risk estimated in all the reported studies from India ranged from E-02 to E-04, showing all the areas are at high risk of cancer for both adults and children. Thus, the high level of BaP might be due to the dominant presence of very high anthropogenic activities like vehicular emissions, diesel combustion, coke and biomass burning, etc. (Zhang et al. 2021). At the same time, the seasonal variation of BaP level in street dust is also considered. Studies from Durgapur, Guwahati and Asansol have been compared with the present study. The BaP level of current studies varies from 2.4 times to 11.6 times higher than those reported in the street dust of Guwahati in pre-monsoon, monsoon and post-monsoon. In the case of Asansol

and Durgapur, the seasonal variation in BaP concentrations is almost similar to 1.6 times lower than the seasonal BaP values of the present study. Thus, for seasonal variation, elevated levels of BaP in the street dust of Raniganj could be from several human activities besides point sources. A high amount of traffic load, several industrial activities, the presence of coal mines, and indoor and outdoor cooking activities might lead to high BaP content. Biomass burning, coke and coal combustion, vehicular emissions, wood combustion, petroleum, diesel and gasoline combustion are some major pyrogenic contributors of BaP in the street dust of the entire Raniganj area (Hayakawa 2024, Kumar et al. 2024, Ali et al. 2021). Like other studies from Dhanbad, Asansol and Durgapur, the BaP content in street dust may increase the chances of exposure and associated health risks to humans living within this region.

The analysis of the global distribution of BaP concentration and its associated risk for human cancer was conducted on a regional basis using available data (Supplementary Table 2, Figs 6 and 7). Most studies in Asia were conducted in China, followed by Iran. The highest concentration of BaP was reported in Anshan City, China, at 12,500 $ng.g^{-1}$ (Han et al. 2009), followed by Nanjing with 3,020 $ng.g^{-1}$ (Zhen

et al. 2020) and Shenzhen with 3,089.07 $ng.g^{-1}$ (Ning et al. 2023). Such a concentration is many-fold greater than that recorded in the present study. The lowest BaP concentration observed in China was in Huanggang City at 67.40 $ng.g^{-1}$ (Liu et al. 2019), which was much lower than the values recorded in Raniganj. Among all the studies, Anshan had the highest cancer risk, with a magnitude of E-01 for both adults and children. Other studies from China have also indicated an elevated cancer risk among residents.

In Iran, maximum and minimum BaP concentrations were reported in Bandar Abbas and Tehran, respectively (Keshavarzi et al. 2018, Saeedi & Salmanzadeh 2012). The BaP level in Karaj City (278.10 $ng.g^{-1}$) (Qishlaqi & Beiramali 2019) was comparable to that in this study, unlike most other Iranian studies, which reported lower concentrations. The total cancer risk for both adults and children in Iran ranged between E-01 and E-05, indicating risks from very high to moderate in the population.

In Vietnam, Anh et al. (2019) found that BaP concentrations and ILCR values were similar to those found in Raniganj, India. In contrast, studies conducted by Zhen et al. (2020) in Japan, Taiwan, and Myanmar, along with Lee et al. (2023) in Daejeon Metropolitan City, South

Table 3: BaP concentration in the street dust and cancer risk from different cities in India.

| Location	Concentration of BaP [$ng.g^{-1}$]	Cancer risk		Year of the Work (sampling)	Reference
		Adult	Child		
Raipur, Chhattisgarh	1988±478	2.19E-02	1.97E-02	2008-2015	Nayak et al. 2023
Bhilai, Chhattisgarh	6869±880	7.56E-02	6.82E-02		
Korba, Chhattisgarh	7094±819	7.80E-02	7.05E-02		
Durgapur (Summer)	156±7.44	1.98E-03	1.79E-03	2013-2014	Gope et al. 2020
Durgapur (Monsoon)	174±11.9				
Durgapur (Winter)	212±22.3				
Dhanbad	531±21	5.84E-03	5.27E-03	2016	Tarafdar & Sinha 2019
Dhanbad	349±71	3.84E-03	3.47E-03	2012	Masto et al. 2019
Asansol (Summer)	134±45.8	2.68E-03	2.42E-03	2013-2014	Gope et al. 2018
Asansol (Monsoon)	229±25.6				
Asansol (Winter)	369±64.8				
Guwahati city (Monsson)	29.3±35	4.88E-04	4.41E-04	2011-2012	Hussain et al. 2015
Guwahati city (Post-monsoon)	29.0±21				
Guwahati City (Pre-monsoon)	74.9±112				
Raipur city, Chhattisgarh	651.4	7.17E-03	6.47E-03	2010	Patel et al. 2015
New Delhi	62	6.82E-04	6.16E-04	2012-2013	Tue et al. 2014
Bangalore	58	6.38E-04	5.76E-04		
Raniganj (Winter)	336.28±93.43	2.89E-03	2.61E-03	2017-2018	Present study
Raniganj (Summer)	181.90±76.46				
Raniganj (Monsoon)	269.17±87.83				
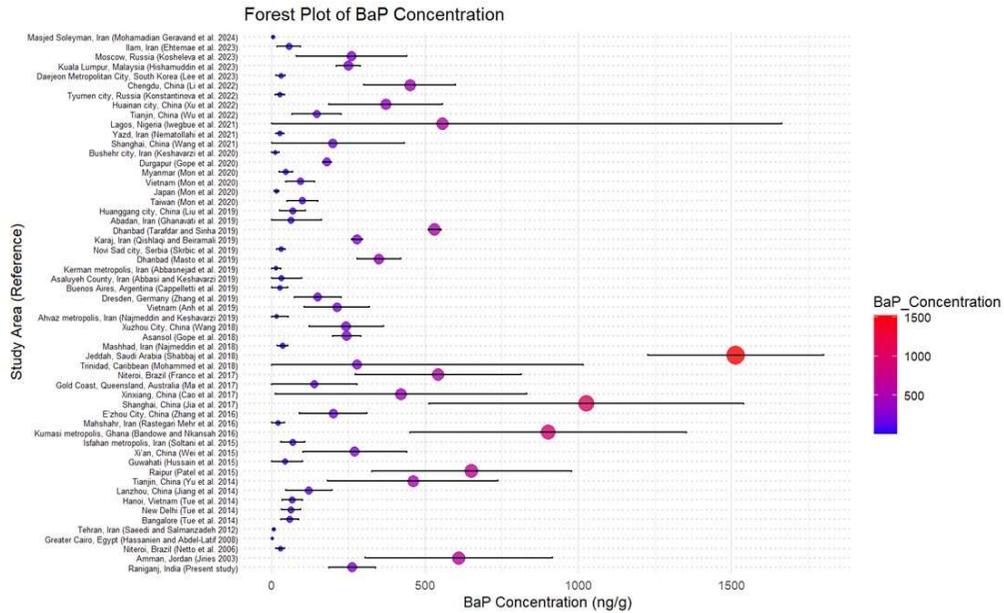
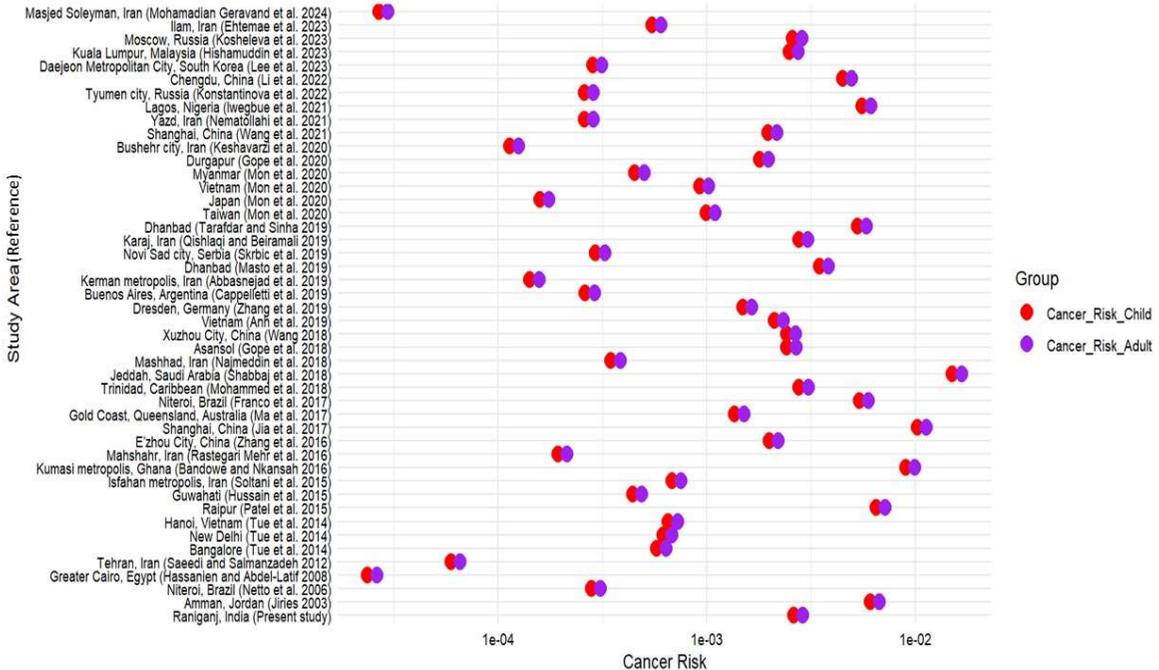Fig. 6: BaP concentrations in street dust from different cities across India and worldwide.

Fig. 7: Cancer risk (child and adult) in street dust from different cities across India and worldwide.

Korea, reported substantially lower BaP levels and cancer risks than those reported in the present study. Nevertheless, studies from Jeddah, Saudi Arabia, by Shabbaj et al. (2018), from Tokyo, Japan, by Khanal et al. (2018), and from Ulsan, South Korea, by Lee and Dong (2010), found the highest BaP concentrations compared to the present study (1,513 ng.g^{-1}, 2,100 ng.g^{-1}, and 6,300 ng.g^{-1}, respectively).

These concentrations correspond to higher cancer risk estimates, indicating a possible health hazard for resident populations.

Four studies were conducted in Europe. One study executed by Kosheleva et al. (2023) in Moscow, Russia, recorded BaP concentrations similar to those of the present study, while the rest reported lesser amounts (Konstantinova et al. 2022, Škrbić et al. 2019, Zhang et al. 2019).

As an African Country, two different studies from Nigeria, one study from Egypt, and three different studies from Ghana were reported. A relatively high concentration of BaP was recorded in Nigeria, Ibadan, at 2,580 ng.g^{-1} (Yusuf et al. 2022). Kumasi Metropolis, Ghana, recorded the highest BaP concentration at the worldwide level, which proved to be 27,900 ng.g^{-1} (Essumang et al. 2006), exceeding levels in Bandar Abbas, Iran. The ILCR figures for African populations ranged from E-01 to E-05, indicating an elevated to moderate risk of developing cancer.

In the Americas, Trinidad, Caribbean (Mohammed et al. 2018), reported BaP similar to the current study, but studies conducted by Cappelletti et al. (2019) and Netto et al. (2006) in Argentina and Brazil, respectively, reported a far lower concentration of BaP in street dust and lower cancer risk estimates as compared to the values obtained for Raniganj.

The global analysis of BaP concentrations and the respective cancer risks exhibited a stark regional trend, with total cancer risk values ranging from E-01 to E-05, indicating a moderate to severe potential risk to human health. Therefore, continued environmental monitoring and the implementation of effective regulatory policies to mitigate the health hazards of BaP exposure are necessary.

LIMITATION AND FUTURE PROSPECTS OF THE STUDY

Several factors limit the present study: i) it only accounts for three seasonal periods (summer, monsoon, and winter) that might not fully represent the temporal variation of BaP concentrations. A more extensive temporal study with monthly sampling over several years would give a better insight into seasonal and inter-annual trends. ii) The number of samples (n = 15) can potentially reduce the spatial resolution and statistical strength of the findings; a larger number of sampling points could improve the representativeness and reliability of BaP monitoring of street dust. Moreover, source apportionment analysis by Principal Component Analysis (PCA) was not conducted, which limits the possibility of identifying the potential sources of BaP in the studied area.

Despite these constraints, the research offers significant guidance for future studies. Monte Carlo simulations are suggested to be integrated in order to evaluate uncertainty in human health risk assessments.

CONCLUSIONS

The present study highlights the spatial and seasonal variation of BaP levels in the street dust of Raniganj. The mean concentration of BaP in the study area was 262.45±

75.55 ng.g^{-1}, which might pose a risk of exposure to the residents of this area. In winter, summer and monsoon, the highest value was observed in site 9, which is a coal mine area. There was a noticeable variation in the mean total BaP levels in the street dust collected from various land use types in Raniganj. A substantial seasonal variation of BaP level was observed here, which was found to be in the order of winter (336.28 ng.g^{-1}) > Monsoon (269.17 ng.g^{-1}) > summer (181.90 ng.g^{-1}). The carcinogenic value and HI of the study area increased in the following order: residential area < commercial area < industrial area < coal mine area < busy traffic area. The average overall cancer risk value for children and adults was 2.61E-03 and 2.89E-03, respectively, describing the presence of a high risk of cancer. The mean HI value for children was 3.42, whereas for adults it was 2.31. Both values indicated the occurrence of a moderate level of health risk. Increased vehicular emissions, indoor and outdoor heating and cooking activities, and changes in several meteorological conditions during winter may cause a higher BaP load in street dust. To study the overall impact of BaP on the environment and human health, it is crucial to concentrate on its sources, characteristics, fate in the environment, pathways of exposure, mode of toxicity and existing regulatory controls so that government agencies and policymakers can initiate new effective policies to control automobile and industrial emissions, limit its exposure, safeguard human health and reduce the related risks. Our study will help to understand the exact scenario of BaP contamination in the Raniganj area so that effective precautionary measures can be taken by the governing body to reduce the exposure risk and to protect the health of the residents of this area from BaP contamination. For precautionary self-protection, protective masks are suggested to be worn by resident populations to minimize inhalation exposures to BaP in ambient dust. Further, enhanced indoor air circulation is recommended to minimize the concentration and accumulation of PAHs in indoor environments and, thus, lower potential health threats of long-term exposure.

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