



Research Article

A comprehensive high-resolution gridded emission inventory of anthropogenic sources of air pollutants in Indian megacity Kolkata



Poonam Mangaraj¹ · Saroj Kumar Sahu¹ · Gufran Beig² · Ravi Yadav³

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Abstract

In this study, we present a first-ever effort made to develop an ultra-high-resolution gridded emission inventory (i.e. $\sim 0.4 \text{ km} \times \sim 0.4 \text{ km}$) for the Indian megacity Kolkata. As the rising demand for fossil fuels based energy along with the spread of urban corridors have forced the anthropogenic activities to a mounting level, therefore determining the sources responsible is of paramount importance. This has worsened not only the regional air quality but also has an indirect effect on the global air quality. The spatial and temporal variation of the source requires an accurate estimation of the surface emission which is the most essential parameter to study the air quality, that positively has been fulfilled in this study. The annual emission for 2020 is calculated to be 37.2 Gg/yr of $\text{PM}_{2.5}$, 61.4 Gg/yr of PM_{10} , 222.6 Gg/yr of CO, 131.3 Gg/yr of NO_x , 60.3 Gg/yr of SO_2 , 120.4 Gg/yr of VOC, 9.5 Gg/yr of BC and 16.8 Gg/yr of OC that prevails in the toxic air of megacity Kolkata. The present surface chemistry dataset will be the first line of detailed information regarding emission hotspots in the megacity that could be used as important tool for clean air mitigation strategies, input into the air quality modeling study to tackle environmental issues, and public health.

Article Highlights

- Identification of sources of pollutants through spatially resolved high-resolution inventory in megacity Kolkata.
- Unlike transport and industrial sector, municipal solid waste burning has emerged as another big source.
- Present information is vital for policy making to mitigate air quality issues and modeling studies.

Keywords Anthropogenic sources · Emission inventory · Megacity · Air quality

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✉ Saroj Kumar Sahu, saroj.bot@utkaluniversity.ac.in | ¹Environmental Science, Department of Botany, Utkal University, Bhubaneswar 751004, India. ²National Institute of Advanced Studies (NIAS), Indian Institute of Science (IISc) Campus, Bangalore 560012, India. ³Ministry of Earth Sciences, Indian Institute of Tropical Meteorology, Pune 411008, India.



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1 Introduction

In last couple of years the whole world has been encountering an epic wave of urban growth where the upsurge in the urban population has led to a rise in the number of megacities i.e. urban agglomerations with a population exceeding 10 million over the past few decades [1–4]. At the same time most of megacities as well as metropolises have emerged as key zones for the deterioration of air quality [5–7]. The worsening of air quality is a major concern in megacities due to its accelerating urbanization, booming industrialization, and their associated anthropogenic activities that lead to the emission of critical pollutants. It is presumed that around 50% of the global populace would be residing in urban area by 2030 and India is to add up to 416 million urban dwellers to its prevalent population by 2050 [8]. Moreover, recently United Nations Environment Programme has estimated that, globally, ~ 1.1 billion people inhale unhealthy air. Poor air quality is the inception of global climate change directly or indirectly and acts as a catalyst to the mortality rate. The consequences include a myriad of acute and chronic illnesses, such as chronic bronchitis, asthma and chronic obstructive pulmonary diseases [9], emphysema (respiratory disorder), circulatory mortality [10], lung cancer, ischaemic heart disease [11] and cerebrovascular diseases [12]. The Global Burden of Disease (GBD) database, states that ~ 4.9 million premature deaths globally occur due to air pollution [13]. Air pollution has been ranked fourth leading global cause of mortality [14].

Indian megacities have been persistently facing challenges related to air pollution and hitting the headlines. India is also home to 21 polluting cities that are listed among the world's top 30 polluted cities [15]. Over the past years, the dramatic expansion in population density, commercial zones, and industrial areas has transformed the lifestyle with increased use of automobiles, intense demand for fossil fuels, bio-fuels, and numerous human-induced activities have degraded the air quality in megacities [5, 16–19]. These hazardous exhausts in megacities restrain a complex mixture of multi-pollutants in elevated concentrations. The diverse unattended and unorganized sources keep on varying spatially and temporally, where the accountability of pollutants is having least priority or being neglected. Therefore, Indian megacities have remained all-time high as the most polluting cities in the world and have borne the brunt, both in terms of health and economic prejudice. In order to understand the ambient air quality over Indian megacities, an accurate estimation of rate of anthropogenic emission of the air pollutants is of great significance. As air pollutants are emitted into the atmosphere from variety of individual sources and processes, therefore, practically it is impossible to measure

each emission source individually. In such hostile context, Emission Inventory (EI) proclaims to be an essential component to our understanding of air quality and atmospheric chemistry.

The consequences of air pollution have been typically a regular event in Indian megacities where the prominent national capital such as Delhi, have always been focused and remained in the spotlight most of the time. Unquestionably, Delhi has been facing the poor air quality all along and has always taken over the front pages internationally. Nevertheless, Kolkata is another megacity in Eastern India which is also considered as one of the oldest metropolises that has been encountering mounting levels of air pollution. Over the past twenty years, the pollution level has been reaching its worst forms, especially in the winters [20–24]. It has also been left unaddressed most of the time but the city is experiencing a phase of rapid deterioration of air quality. According to the West Bengal Pollution Control Board (WBPCB) and Central Pollution Control Board (CPCB) the monitoring stations of Kolkata city have also been observing a high ambient PM (Particulate Matter), NO_x (Nitrogen Oxide) pollution exceeding the national standards continuously. Unlike Delhi, limited studies have been focused on Kolkata's pollution and its impact on air quality. Only a few earlier studies (like, [25–27]) have demonstrated their approach to assess the air quality in and around Kolkata through measurement and limited emission work. It is found that Kolkata has been least focused when it comes to air pollution studies. On most occasions, the studies have addressed major sector-specific limited pollutant studies with variance in the domain of interest. At the same time, these studies are targeted for older base years like 2004, 2011, and 2015 respectively. With changing lifestyle and social factors, energy consumption pattern in megacity changes rapidly with time and so does the sources of air pollutants, which have larger spatial and temporal variability. Framing city specific air pollution management policy depends profoundly on the basic understanding as well as insight of the several sources that have predominated in the urban area towards deteriorating air quality issues. Therefore, the prime and foremost attempt towards initial mitigation effort begins at comprehensive study on identification of local sources and its quantification.

Keeping a note of the limitations and the need for better understanding the sources of air pollutants, this paper is set forth to assess the emission of major air pollutants from all possible major/minor sources. This study unfolds a thorough surface-emission dataset for the base year 2020 that represents the data compiled for April 2019 to March 2020. This study includes ~ 17 sectors focusing on eight major pollutants involving particulate matter—PM_{2.5} and PM₁₀, carbon monoxide (CO), NO_x, sulphur dioxide (SO₂), volatile organic compounds (VOC_s), black carbon (BC) and organic carbon (OC). In this article, a multi-pollutant high-resolution gridded

(~0.4 km × ~0.4 km) emission inventory for the Indian megacity Kolkata has been developed whose outcomes would be an essential tool in formulating new environmental mitigation strategies and policies to improve air quality and public health.

2 Methodology

2.1 Target region

The megacity Kolkata, formerly known as Calcutta is a city of trade, transport, and manufacture, is another dominant urban center of East India and is regarded as the cultural capital. It is situated towards the South-East of West Bengal state (Fig. 1), at an altitude of ~17 feet above mean sea level. The coastline of the Bay of Bengal lies at a distance of ~60 km to the South. It is located at 22.5625°N and 88.3531°E in the Indian subcontinent. The megacity Kolkata falls under the jurisdiction of the Kolkata Municipal Corporation (KMC), having an area of ~206 sq km. It is the only region in West Bengal, which is highly urbanized as compared to other cities in West Bengal [28]. The city has an extended metropolitan population of over 14.9 million as of 2020 and continues to struggle with the problems of the fast conurbation, far-reaching industrialization, rapid automation, and traffic congestion. To account for all the existing major/minor anthropogenic activities in this densely populated domain, it remains our area of interest.

2.2 Sources of air pollution in Kolkata

The sources of air pollutants in cities are mostly anthropogenic and taking a note of the diversity of sources; the present study has taken nearly 17 major and minor sources into account that are certainly responsible for the city's air pollution issues. The database of activity data for individual sources is compiled from an authentic primary as well as secondary source. Due to inadequate situation, no field campaign was carried out to compile primary data for slum, residential, transport, and street vendors, etc. In such adversity, to experience the megacity scenarios, the primary data collected during field campaigns under the SAFAR program over four major/megacities i.e. Delhi, Mumbai, Pune, and Ahmedabad where the primary data, as well as the emission estimation, are published through Ministry of Earth Sciences (MoES) reports (viz. [5, 29–33]) are being adopted in a few sectors to fill the data gap like vehicle travel pattern, slum cooking pattern, street vendor cooking activities, etc. A list of sources of activity data is also provided in supplementary data Table S1. The assembled information was closely checked for quality before being used in emission estimation in the present study. For any city-specific high-resolution secondary activity data, it can be accessed via published scientific and government reports/data banks. Moreover, these campaigns witnessed the current condition of Indian megacities. Therefore, to the sectors where activity data is extremely limited, a similar orientation of data analysis is implemented for Kolkata city.

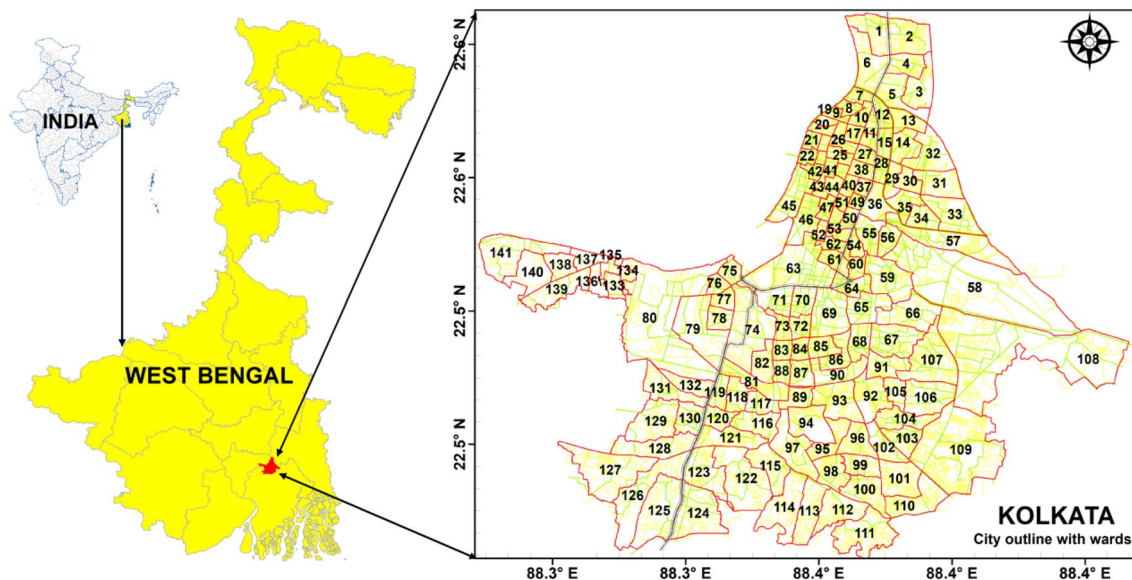


Fig. 1 Area of Interest (Kolkata with ward numbers)

2.2.1 Road transport

In Kolkata, vehicle traffic has always remained a dominant source of pollution and with rapid modernization, the demand for motorization remains a key objective [34]. In addition to this, growth in the number of private vehicle segments has also transcended lately. According to the Ministry of Road Transport and Highways [35] the number of vehicles registered in Kolkata alone was ~0.4 million in 2010 that grown up to ~1.8 million vehicles as of 2020 March that indicates around a four-fold rise within just a decade. For public modes of transport, the city has autos rickshaws (three-wheelers), taxis, buses, trams, metro, and local trains. In this study, we have classified the whole road transport system broadly into eight categories:- Two-wheeler (2 W), Three-wheeler (3 W), Bus, Personal Car (P Car), Commercial Car (C Car), Heavy Commercial Vehicle (HCV), Light Commercial Vehicle (LCV), and Multi-utility Vehicle (MSLV). Two-wheelers appear to contribute ~71% to the total number of vehicles, which is relatively huge. Furthermore, the personal and commercial cars bestow ~12%, heavy and light commercial vehicles ~11%, and the remaining ~5% are owned by three-wheelers, buses, and multi-utility vehicles. Around 49% of vehicles belong to >15 years old category as to load of aging vehicles. The per-day distance travelled by individual vehicle category is an important modulating factor that decides the intensity of traffic in a particular region and associated pollution load. Therefore, Vehicle Kilometres Travelled (VKT/day) was adopted from primary data collected as per real-time megacity scenario during SAFAR

emission inventory campaigns. These campaigns held at various cities illustrate the arena of a metropolitan city. The specific vehicle category and the type of fuel being used were recorded from the official source like the Transport Department of West Bengal and the Ministry of Road Transport and Highways. Currently, Bharat Stage-IV (BS-IV; equivalent to Euro-IV) norms have been implemented for on-road vehicular emissions in Kolkata since 2010. According to the Motor Vehicle Amendment Rule, Govt. of India, BS-VI norms (equivalent to Euro-VI) have been made mandatory for all new registered on-road vehicles only from April 2020. As reported by the Ministry of Road Transport and Highways, vehicles older than 15 years are prohibited in Kolkata with effect from 1st April 2022. Despite that, the active fleet of older vehicles registered during 2000–2010 will not comply with the BS-IV norms as of 2015. Furthermore, a fraction of the fleet registered during that period might be still running on the road in 2020 regardless of the phasing-out procedure.

2.2.2 Wind-blown road dust

Megacity Kolkata has been tagged as one of the most unplanned and polluted cities in the world [24]. The increase in vehicular movement on roads is significantly higher than the augmentation in the road network hence, leading to congestion and further contributing to air pollution load [28, 34]. According to the Basic Road Statistics of India [36] as well as digitization of road network over Kolkata city, the total road length was determined to be ~2876 km which includes minor roads (~2152 km),

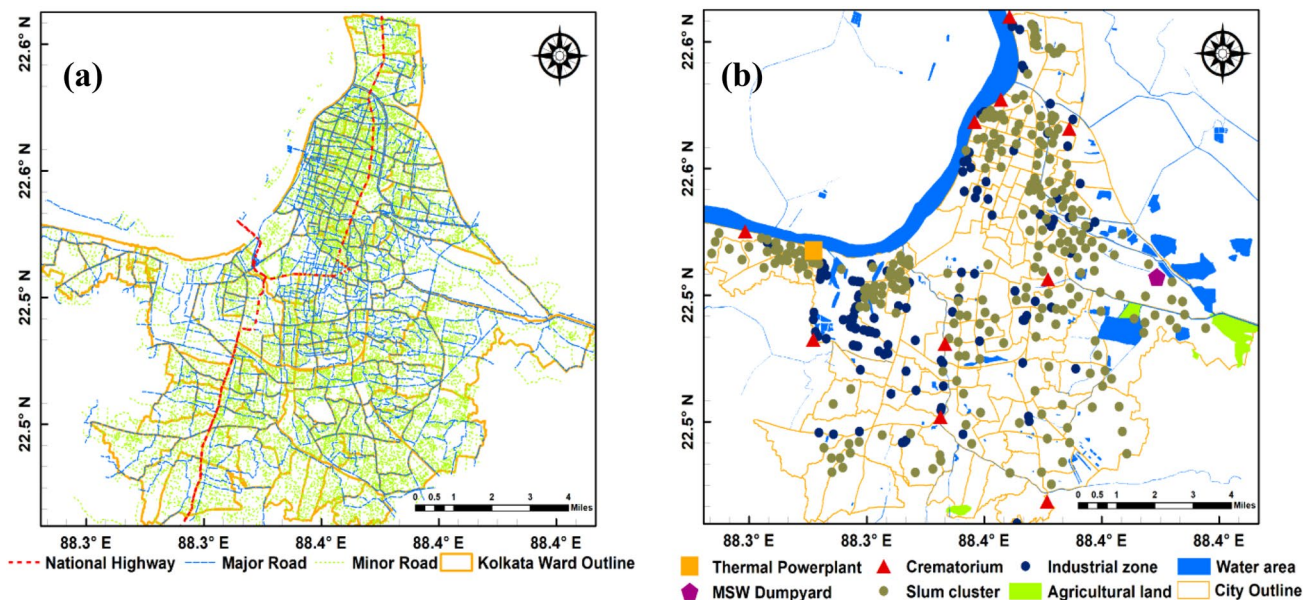


Fig. 2 a Road network in Kolkata and b Spatial location of various types of emission sources

major roads (~684 km), and ~40 km of national plus state highways as shown in Fig. 2a. However, the road space and road condition are down-and-out which is why it has also been termed as a dusty city. The minor road network over the city is compiled and a couple of roads with high vehicle density and slow traffic areas are identified from Google map too. Various case studies report that due to relentless movements of vehicles inside the city, especially the heavy vehicular fleet have resulted in broken and dusty roads. The vehicle-induced road dust resuspension in the city is also dependent on certain modulating factors like the state of pavement, average precipitation days, soil moisture content, silt load, vehicle fleet composition, their average weight and mean vehicular speed. The report of Rainfall Statistics of India, [37] stated that Kolkata received an annual rainfall of 1815.2 mm in 2019–20, with average precipitation days of ~95–100 days. The soil profile of Kolkata tends to be alluvial type due to its geographic location i.e. Indo-Gangetic Plain. Alluvial soil is considered as one of the best soils due to its moisture-retentive capacity. Therefore, the moisture content of the soil was hence decided to be ~8%. Observing the SAFAR city-wise study the surface material silt content for Kolkata was concluded ~11% for paved roads and ~12% for unpaved roads. The average weight (~1.91 tons) were derived from the number of vehicles running on the road and vehicle speed was assumed to be around 15 mph.

2.2.3 Industry

WPCB introduced a new categorization format for the industries with effect from 30th June 2016, where the industrial units of West Bengal have been classified into four different categories depending upon their pollution potential such as:- red (maximum pollution potential), orange (moderate pollution potential), green (low pollution potential), white (have least pollution potential) [28]. According to the sitting policy of WBPCB, the red and orange category industries are not permitted in the KMC except in the industrial estate region with proper pollution control measures and approval from local bodies [28]. Kolkata city includes 986 registered industrial units and 19,482 registrations under the Udyog Aadhaar Memorandum for identification under the Ministry of Micro, Small, and Medium Enterprises (MSME) Kolkata. The city owns several industries like iron and steel, metallurgy, textiles, tanneries, paper, chemicals, engineering, and many others. West Bengal is predominant in developing micro and small-scale industries and most of these units are located in Kolkata [38] where the fuel usage pattern is highly uncertain. Moreover, there is no systematic database for the fuel used by individual industries, so the fuel consumption pattern is adopted as per the national average record.

2.2.4 Thermal power plant

According to the Central Electricity Authority (CEA) of India, currently, there is only one thermal power plant—Southern Generating Station operating in the study domain. It has been operating since 1990. The power plant is operated by the Calcutta Electric Supply Corporation (CESC). It has a total installed capacity of 135 MW with two units of 67.5 MW each. CESC Southern Generating Station is a coal-based thermal power plant. Information regarding the installed capacity, the number of operational units, the technology used from the homepage of CESC Southern Generating Station [39], and coal consumption pattern with the PLF% (plant load factor) was obtained from CEA's daily coal stock and CEA Annual Report [40].

2.2.5 Residential (includes sub-sectors: household, slum, street vendor, crop residue burning, cow-dung, and diesel generators)

After megacity Delhi and Mumbai, Kolkata with an urban population of ~14.9 million ranks the third largest megacity across the country. The total population is assumed to be distributed among 2.9 million households with an average household size of five. Furthermore, according to the KMC, it is estimated that around 1/3rd of the urban population lives in slums/bustees where the access to clear fuel is limited. There are around 5,500 slums across the city [41] distributed in clusters. Khidderpore, Garden Reach, Park Circus, and MG Road, are some of the popular slum localities that are experiencing high slum density. The lack of basic amenities and infrastructure in rural areas is a deficit that compels people to migrate towards the city in search of economic opportunities and stability. So far, the solid fuel used for cooking activity in the households and slums is one of major contributor to air pollution [14]. In addition to this, street vending in Kolkata has become a primitive source of income strategy for the urban poor/slum dwellers and therefore is regarded as a dynamic process in which people engage to construct their livelihood [42]. Various case studies and reports indicate that the city holds more than 0.15 million street vendors who earn their livelihoods by vending. Lack of reliable government statistics with regard to street vendors involved in individual activities in Kolkata is a considered as a data gap. It's practically difficult to take a note of individual vending zone involved in cooking activities leading to air emission. Considering the regional fact that Kolkata happens to be one of the popular cities in street foods, therefore it is assumed that ~50% of the vending activities are held to be contributing in air pollutant emission. Access to clear fuel in the city is limited. According to the Ministry of Petroleum and Natural Gas (MoPNG), the practice of cleaner fuels (LPG)

in India has become much frequent since 2012, under the Pradhan Mantri Ujjwala Yojana scheme. However, the utilization of unrefined fuel like coal, wood, crude oil, etc. in the slums zones and vendors has been escalating in terms of air pollution and these unattended sources cannot be neglected [5, 31, 33]. Therefore, relevant information like the type of fuel used, their quantity per capita, and the hours of cooking was adopted from free as well as paid authentic private sources [43] and government sources like the official website of Kolkata Municipal Corporation for ward level population and per capita basic amenities [44]; Department of Food & Supplies, Government of West Bengal for consumer fuel supplies data [45], and SAFAR-campaign reports. The primary data under SAFAR-campaign gives cooking scenarios in a megacity that fulfil the data gap up to a greater extent.

It is pretty well-known that rice is a major crop in West Bengal. Most parts of Kolkata are engulfed by urban expansion leading to the shrinkage of greenery. A case study noticed a decrease in the arable land annually within Kolkata city in the past forty years (1977–2017) [46]. However, cultivation is not a common practice within the core urban region but the peri-urban areas towards the extreme east of Kolkata hold little agricultural space. Therefore, crop residue burning in the urban zone is of little significance. The activity data with reference to crop cultivation area and amount are obtained from free as well as paid authentic government/private portals like ICAR (Indian Council of Agricultural Research) for state-wise crop production [47], Ministry of Agriculture & Farmers' Welfare for crop-wise agricultural statistics [48], MOSPI (Ministry of Statistics and Programme Implementation) for national agricultural statistics [49]. The method for estimating crop residue generation and fraction burnt is adopted from past study Sahu et al. [18]. The agricultural residue generated is also mixed with cow-dung and other raw materials like coal dust and biomass for domestic cooking in rural fringes of the city, especially during winters for boiling water and cooking activity as observed during the SAFAR campaigns. The use of diesel generator (DG) sets as power backup is quite prevalent at large premises of the city like restaurants, hotels, malls, shopping centres, theatres, hospitals, and residential complexes. Along with that according to the Department of Telecommunication (DoT), [50] Kolkata has more than ~50,672 base transceiver stations (BTS) that are run with DG sets for a continuous or alternative source of power. A typical BTS site is well mobilized with a 12–25kWh diesel generator which consumes ~9000–12000L of diesel per year [51].

2.2.6 Other (includes sub-sectors: municipal solid waste burning, construction, incense sticks/mosquito coils/cigarettes, and crematory)

The Kolkata Airport otherwise called Netaji Subhas Chandra Bose International Airport of India serves as the aviation hub for the entire Eastern and North-Eastern India. The spatial position of the airport is located ~10–12 miles away from the city centre. As it does not fall within our domain of interest, therefore aviation sector for Kolkata isn't considered in our study. According to the West Bengal Pollution Control Board and Kolkata Municipal Corporation, the city of Kolkata generates ~4000–4500 metric tonnes of solid waste per day. This bulk of waste is entirely dumped at its only landfill site i.e. Dhapa. Located towards the eastern fringes of the city, this landfill site is spread across ~35–50 hectares and has been functional since the 1980s. Currently, in India ~23% of total municipal solid waste generated is treated, 43% is land-filled and the rest 34% is openly burned to prevent the dumping ground from overflowing with waste [52]. Considering this fact, as there is no municipal solid waste to energy plants within Kolkata city, it was assumed that ~70% of municipal solid waste is dumped and the rest 30% is openly burnt right away. Kolkata's steady urban growth has led to rigorous construction activities of flyovers, roads, building blocks, multi-complexes, etc. contributes as a source of dust. The use of heavy commercial vehicles and multi-utility vehicles like bulldozers, tractors, scrapers, compactors for loading and unloading of construction material, land clearing, demolition, and disposal of debris in a certain way leads to suspension of dust especially PM_{2.5} and PM₁₀ [34]. West Bengal is also one of the leading brick manufacturing hubs. A maximum number of brick kilns are located towards the river basin, which isn't present within the selected city domain for our study.

Despite the fact that few crematoriums these days have shifted to the electrical system in cities, the traditional Hindu funeral pyre system of burning dead bodies is still effective. According to the KMC portal, there are at least 10 crematorium grounds in Kolkata where traditional burning is preferred. To cremate a body by traditional pyre system ~450–550 kg of wood per body is required. It takes ~6 h to burn it down completely, which releases harmful air pollutants [31]. Kolkata very well known as the Cultural capital of India has the largest market of incense sticks [53]. Kolkata keeps celebrating many festivals throughout the year where the burning of incense sticks

is a major part of their tradition. The daily per capita usage of incense sticks was estimated by taking its weight and its composition (45% biomass, 25% wooden chips/bak-hoor 15% coal, 15% resin/jigit) into account, which is vital. The use of mosquito coils has always remained a topic of interest in terms of indoor air pollution [31]. The amount of biomass, wood dust, and charcoal used for making mosquito coils play an important role during combustion that has detrimental effects. Similarly, the practice of smoking tobacco and cigarettes has never been compromised in consumption for eons. As per the World Health Organization (WHO), India is home to ~ 120 million smokers, and each year more than 10 million die due to tobacco/cigarette consumption. All the essential information like chemical or biomass composition etc. concerning these unorganized minor sectors (incense stick/mosquito coal/tobacco) has been referenced from Cohen et al. [54] and Kumar et al. [55]. The spatial locations of all the major sources are highlighted in Fig. 2b.

2.3 Emission estimation methods

Emission factor (EF) is very sensitive parameter that is highly dependent on combustion type, fuel classification, its chemical composition, and its usage and emission control device. These factors have a significant role in modulating the quality of inventory data preparation. The emission factors used for different fuel types in our estimations for the industrial, thermal power plant, residential, and other commercial sectors are taken from several sources suitable to Indian condition. These factors are experiment-based numbers conducted by government agencies or government-authorized non-governmental organizations and published in research articles. Vehicular emission sources are not uniform, as they generally consume varieties of fuel (gasoline, diesel or compressed natural gas) depending upon their engine type (2-stroke or 4-stroke) and norms (Bharat Stage- I, II, III or IV etc.) implemented. So, emission factors developed by the Automotive Research Association of India (ARAI) are used in our study, where Indian driving cycle, the age of vehicles, and engine technology are taken into consideration for developing EF. These values have also been used in our recent studies [7, 51, 56]. A complete database of EFs can

A comprehensive methodology for emission estimations involves an emission factor-based approach where, the emission of a specific pollutant from an individual source is a product of activity data and EF. Therefore, we have followed a “bottom-up” approach for estimating emissions. The equations used are similar to that adopted by Klimont et al. [57], Bond et al., [58] and in our previous works [7, 18, 59, 60].

The total emission from all the sources was calculated as per Eq. (1). However, for the road transport sector of India the estimations were specifically calculated as per Eq. (2) due to technology-specific vehicular emission factors derived by ARAI [61] and CPCB [62]. The wind-blown road dust is another important sector, which possesses modulating factors that influence the emission estimation. Therefore, Eqs. (3) and (4) are used for estimating emission due to vehicle movement on paved and unpaved roads is one of the major sources of PM.

$$T = \sum_x \sum_y F_{x,y} \left[\sum_z Ef_{x,y,z} A_{x,y,z} \right] \quad (1)$$

where x, y, z = sector, fuel type, technology; T = Total amount of Emission; F = sector specific fuel amount; Ef = Country specific technology emission factors; A = amount of fuel associated with particular technology where $\sum A = 1$ for each kind of fuel and sector.

$$T_c = \sum (V_l \times D_l) \times Ef \quad (2)$$

where, T_c = Total Emission of pollutant; V_l = Category-wise vehicle number; D_l = Distance travelled by each vehicle type (VKT/year); Ef = Fuel and vehicle type specific emission factors.

$$\text{For Paved Road Dust : } - T_p = [k(st/2)^{0.91}(wt)^{1.02} + C] \left(1 - \frac{pt}{4N} \right) \quad (3)$$

where, T_p = particulate EF (w.r.t. units matching the units of k); k = particle size multiplier for particle size range and units of interest (g/VKT); st = silt load on road surface (g/m²); wt = average weight of the vehicle (tons); pt = precipitation days with at least 0.254 mm annually; N = total number of days in the averaging period; C = EF for 1980's fleet of vehicles' exhaust, brakes and tire wear.

$$\text{For Unpaved Road Dust : } - T_{up} = \left\{ \left[k \left(\frac{st}{12} \right)^a \left(\frac{VS}{30} \right)^d / \left(\frac{m}{0.5} \right)^c - C \right] * [(365 - pt)/365] \right\} \quad (4)$$

be found in supplementary data Table S2 with detailed reference.

where, T_{up} = size-specific EF (lb/VMT); st = surface silt load in %; m = surface moisture content in %; VS = average vehicle speed (mph); C = EF for 1980's fleet of vehicles' exhaust,

brakes and tire wear; pt = precipitation days with at least 0.254 mm annually; k , a , c and d are empirical constants.

After emission estimation, efforts were made to display the emission spatially correct. Therefore, a Geographic Information System (GIS) based approach is used for spatial distribution of emissions over selected domain. We have incorporated different layers of fine resolution spatial proxies to grid the emission values to our required resolution. By way of illustration, for emissions from wind-blown road dust and road transport sector included- layers of road networks including national and state highways, major and minor roads; for domestic sectors—population density of village level, the urban spread of the grid; other sectors—data on the economic activity like that of hospitals, market complexes, hotels, residential blocks and commercial zones are used as a proxy to determine the emission both spatially and temporally. Emission loads of the industrial sector and power plant are allocated to the particular grid where the source is present, hence that exact spatial locations are designated with the best accuracy. The details regarding the spatial proxies considered for the estimation and gridded emission distribution is provided in the supplementary information. Comprehensively, Kolkata city's geographical region is covered by 1181 grid cells, each having a resolution of $\sim 0.4 \text{ km} \times \sim 0.4 \text{ km}$.

3 Results

3.1 Annual emission

Present findings provide a detailed accountability of annual emission load from all possible sectors responsible for worsening the ambient air quality in Kolkata. The annual emission of the targeted pollutants from all the sectors include 37.2 Gg/yr of $PM_{2.5}$, 61.4 Gg/yr of PM_{10} , 222.6 Gg/yr of CO, 131.3 Gg/yr of NO_x , 60.3 Gg/yr of SO_2 , 120.4 Gg/yr of VOC, 9.5 Gg/yr of BC and 16.8 Gg/yr of OC for the base year 2020. The pollutant-wise sub-sectoral breakup of emission load is tabulated in Table 1.

3.2 Spatial distribution and sectoral contribution

The estimated emissions for all the eight major pollutants are analysed competently, where the spatial patterns for all pollutants are more and less similar due to the same source of emission. To avoid overcrowding and anarchy, we have specifically focused on elaborating the spatial distribution of one particulate pollutant (PM_{10}) and one gaseous pollutant (NO_x) which will represent the source of pollutants in much comprehensive manner as given below.

Table 1 Sector-wise annual emissions (in Gg/yr) for Kolkata

Sectors	$PM_{2.5}$	PM_{10}	CO	NO_x	SO_2	VOC	BC	OC
Wind-blown Road Dust	1.051	9.399	NA	NA	NA	NA	NA	NA
Transport	12.050	13.770	135.390	84.727	16.25	119.787	4.878	7.658
Industry	6.816	10.826	3.703	27.768	35.225	NA	1.665	NA
Power Plant	0.296	1.133	0.030	1.597	5.765	0.001	0.015	NA
Household	0.427	2.149	7.273	1.738	0.307	0.036	0.082	0.541
Slum	1.115	3.431	14.727	2.104	1.100	0.089	0.278	1.131
Street Vendor	0.825	1.181	5.464	0.708	0.368	0.031	0.075	0.431
Crop Residue Burning	0.423	0.469	4.452	0.175	0.078	0.416	0.036	0.173
Cow-Dung	0.463	0.579	3.927	0.075	0.018	0.032	0.05	0.302
Diesel Generators	3.652	4.566	2.06	9.537	0.634	NA	1.867	NA
Municipal Solid Waste Burning	5.979	6.439	30.813	1.720	0.230	NA	0.460	5.979
Construction	1.684	4.21	NA	NA	NA	NA	NA	NA
Incense Sticks/Mosquito Coils/ Cigarettes	1.919	2.362	10.013	0.597	0.325	0.039	0.147	0.301
Crematory	0.506	0.632	4.767	0.578	0.008	0.025	0.045	0.322
Grand Total (Gg/yr)	37.206	61.144	222.617	131.325	60.307	120.455	9.599	16.839

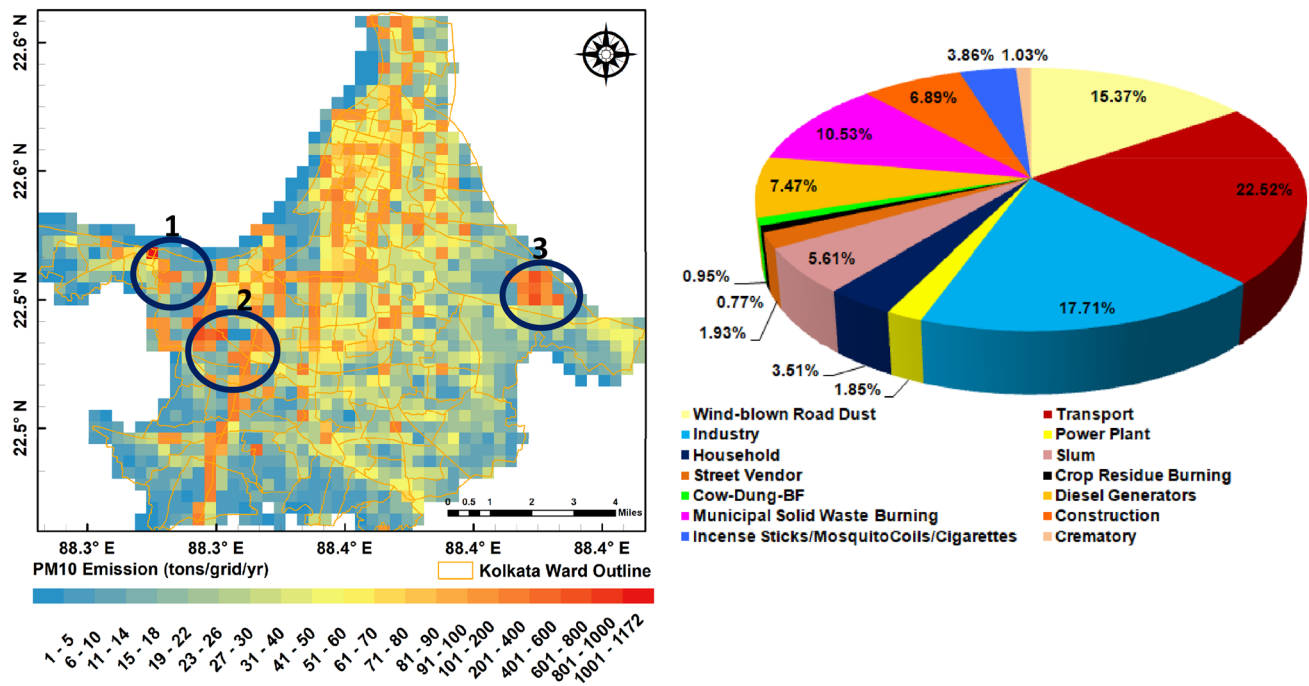


Fig. 3 Gridded annual PM₁₀ emission and its sectoral contribution

3.2.1 Particulate pollutant (PM₁₀)

Spatial distribution of emission illustrated in Fig. 3 focuses on the total PM₁₀ as a whole (~ 61.1 Gg/yr) and its sectoral relative contribution. It is observed that maximum PM₁₀ emission ranged from 200–1172 tons/grid/yr and are prominent in the national highway and major roads. A minimum emission ranging from 50–100 tons/grid/yr is spatially scattered across the Central region of Kolkata. The grid with the highest emission ~ 1172 tons/grid/yr was found towards the Western part of the city, where many industrial clusters and thermal power plant near the Garden Reach area. Along with this the major roads like Tartala Road, Garden Reach Road and Paharpur Road also carried a huge load of PM₁₀ (~ 250–600 tons/grid/yr) due to high vehicular emission and road dust resuspension and as well. As these roads are linked to the main junctions of industrial and power plant area, they tend to experience large no. of HCVs and LCVs movement used for supply of raw material (coal). The gross weight of the HCVs and LCVs while carrying the raw material affects their speed, which triggers the vehicular exhaust emission. Movement of heavy vehicle on poor road condition and vehicle-induced turbulence are the prime factors for road dust resuspension. Grid with second highest emission peak ~ 774 tons/grid/yr was spotted near the Park Street Area and Minto Park Area towards the Southwest of the city, that has metal and electrical manufacturing industrial clusters. This area also has a flyover, near main road and shows heavy traffic

point, rich in residential and commercial activity. The third highest emission (~ 749 tons/grid/yr) was noted near the municipal solid waste burning site at Dhapa, which is the largest and the only garbage dump in Kolkata city. Furthermore, transport sector remained the highest contributor (~ 23%) to total PM₁₀ as shown in Fig. 3. Industry (~ 18%) had the second largest contribution, followed by the wind-blown road dust (~ 15%). Open burning of municipal solid waste contributed ~ 11% to city's total PM₁₀ emission. Low technological cooking practices and other commercial activities in household/slum areas also contribute significantly (~ 10%) to PM₁₀ emissions. Dominant slum pockets located in the areas of Khidderpore, Garden Reach, Park Circus, and MG Road near Burra Bazar and densely populated residential areas like Central Kolkata Bhowanipore, Moulali, Alifnagar Bustee, Park Street Residential Area etc. show as much high emission of PM₁₀ from their domestic cooking and other activities that involve biomass burning. These residential areas are accompanied with commercial cooking activities like street vending which are much scattered across the city. The consumption of raw fuels for cooking practices as discussed in the activity data, is the prime reason why these places equally remain a significant contributor to ~ 7% of the PM₁₀ emission.

Major sector-specific gridded PM₁₀ emission was plotted separately where the spatial pattern of emission load could be observed distinguishably as shown in Fig. 4. We have rearranged it into six major sectors. Transport sector accounts ~ 13.7 Gg/yr as shown in Fig. 4a along with

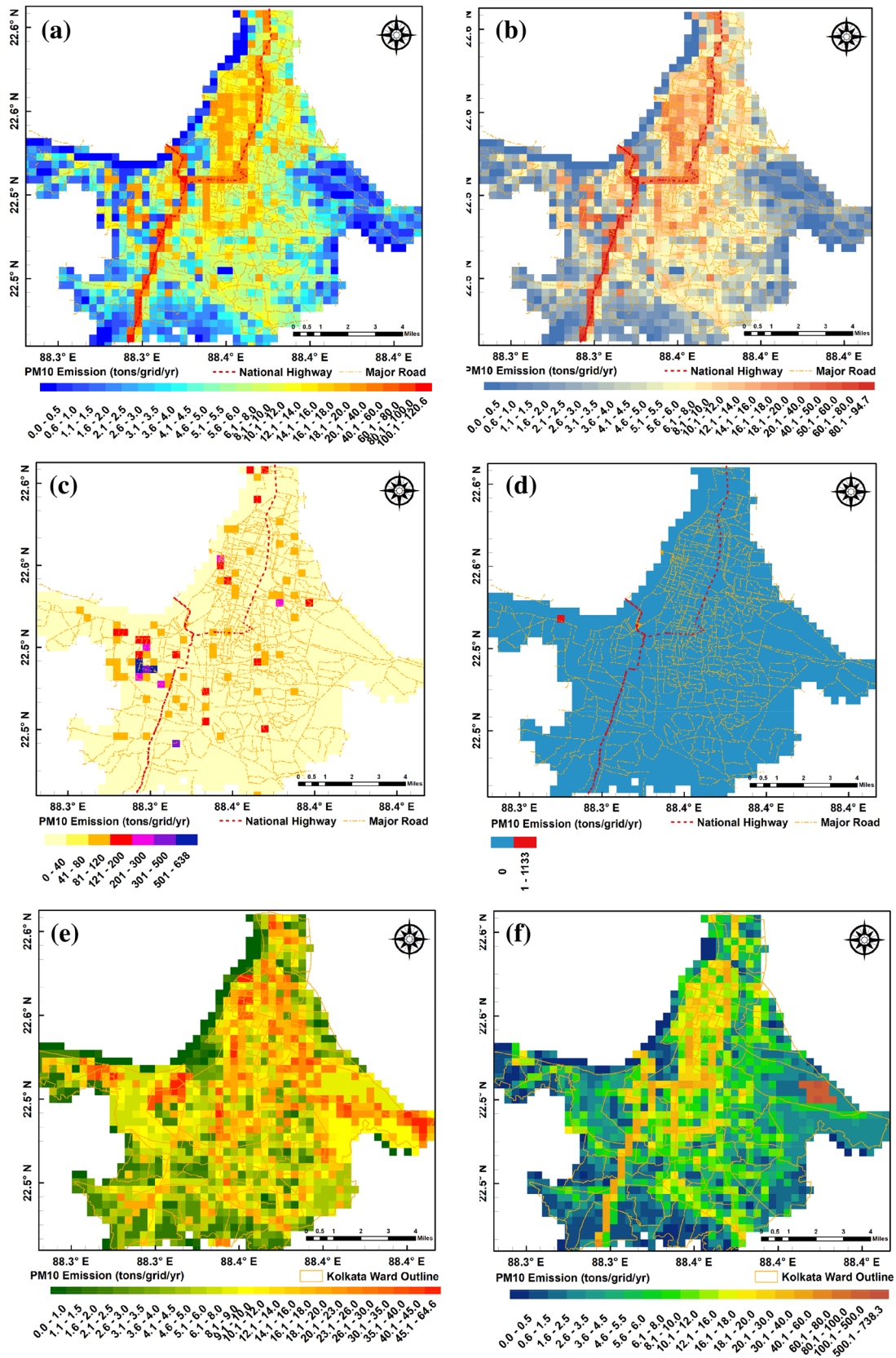


Fig. 4 Sector specific gridded annual PM₁₀ emission from **a** Transport **b** Wind-blown road dust **c** Industry **d** Thermal power plant **e** Residential **f** Others

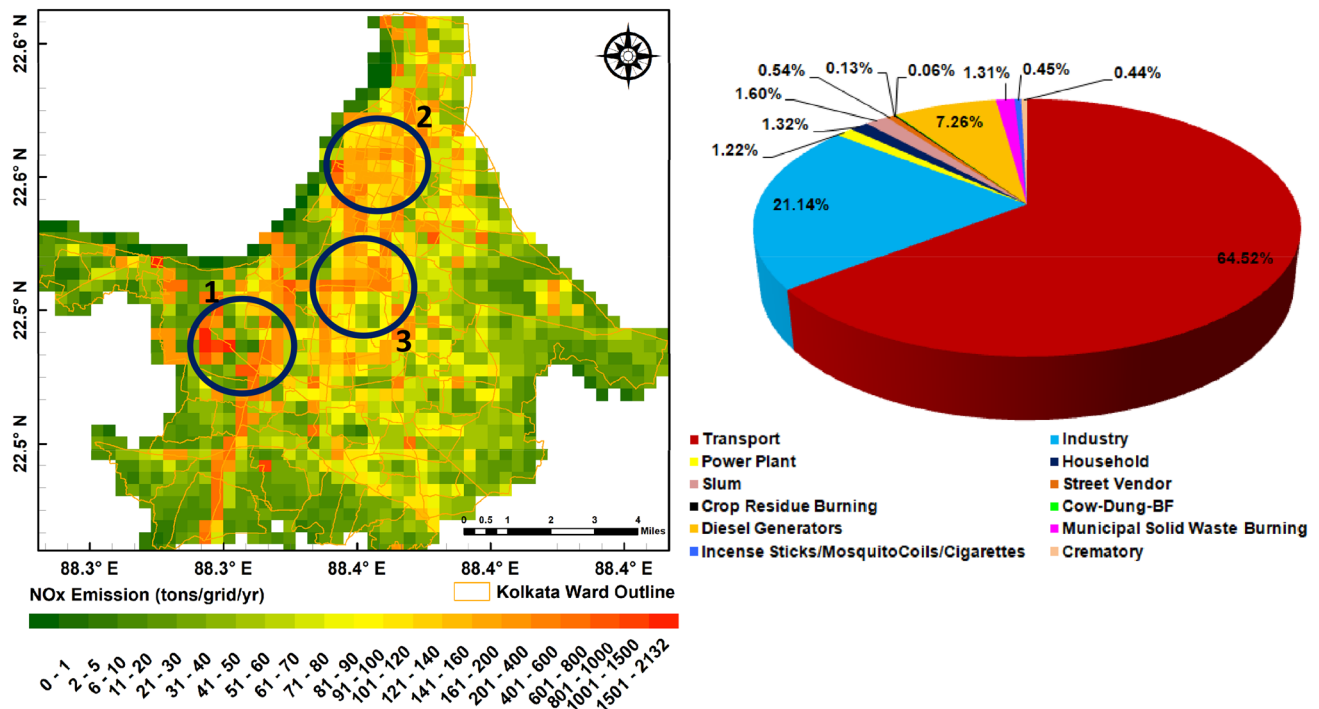


Fig. 5 Gridded annual NO_x emission and its sectoral contribution

wind-blown road dust ~ 9.3 Gg/yr (Fig. 4b); industrial sector ~ 10.8 Gg/yr (Fig. 4c); thermal power plant 1.1 Gg/yr (Fig. 4d), residential sector with ~ 12.3 Gg/yr (Fig. 4e) that included minor sectors like household, slum, street vendor, crop residue burning, cow dung as bio-fuel, diesel generators and other sector with ~ 13.6 Gg/yr of PM₁₀ load (Fig. 4f) which included minor sectors like municipal solid waste burning, construction, incense sticks/ mosquito coils/ cigarettes, and crematory. This present study also concludes that transport sector remains the largest contributor to total PM₁₀ emission as distinctively seen in Fig. 4a where the national highways and major roads hold the highest PM₁₀ emission ranging from ~ 20–120 tons/grid/yr. Some of the highest traffic congestion roads observed in our study includes MG Road, AJC Bose Road, Tartala-Behala Road, and Khidderpore Road etc. This is due to the huge no. of heavy commercial vehicular movement, which alone contribute ~ 38% to total PM₁₀ emission from the transport sector. PM₁₀ load in the order of 4.5–10 tons/grid/yr is spatially scattered throughout the domain. So, it was concluded that a high traffic network associated with low velocity of vehicle that triggers more congestion and directly or indirectly amplifies emissions.

3.2.2 Gaseous pollutant (NO_x)

The total NO_x emission ~ 131.3 Gg/yr and its sectoral relative contribution are portrayed in Fig. 5. A maximum emission in order of ~ 200–2132 tons/grid/yr of NO_x is found over national highway and major road networks connecting to various industrial clusters. The highest emitting grid recorded ~ 2132 tons/grid/yr of NO_x and this gridded patch is confined over Central West Zone, where industrial and transport sector together contributed ~ 80%. These regions were found to have high vehicular and industrial density which makes these zones quite crowded and industrious that can also be observed in Fig. 2(a) and (b). Industrial zones like Tartala Industrial Complex, Khidripore, Tikiapara and Khangrapatti region are spatially located here, where manufacturing industries like those of metal, electrical, chemical, oil and gas etc. are quiet dominant in the clusters. Emission ranging from 150–400 tons/grid/yr was found prominent in two patches towards the Northern part of city, patches in the centre aligned towards the periphery and Southern part of the city. Major traffic roads in this patch includes MG Road, Armenian St Road, Bra-bourne Road, Central Ave Road and Vivekananda Road. Dense road networks drive the large vehicle movements in the above region. A grid level analysis shows that just 10% of grids contribute ~ 48% of total NO_x emission, which are considered to be highly polluted. Sector-specific relative contribution to NO_x emission indicated that, the transport

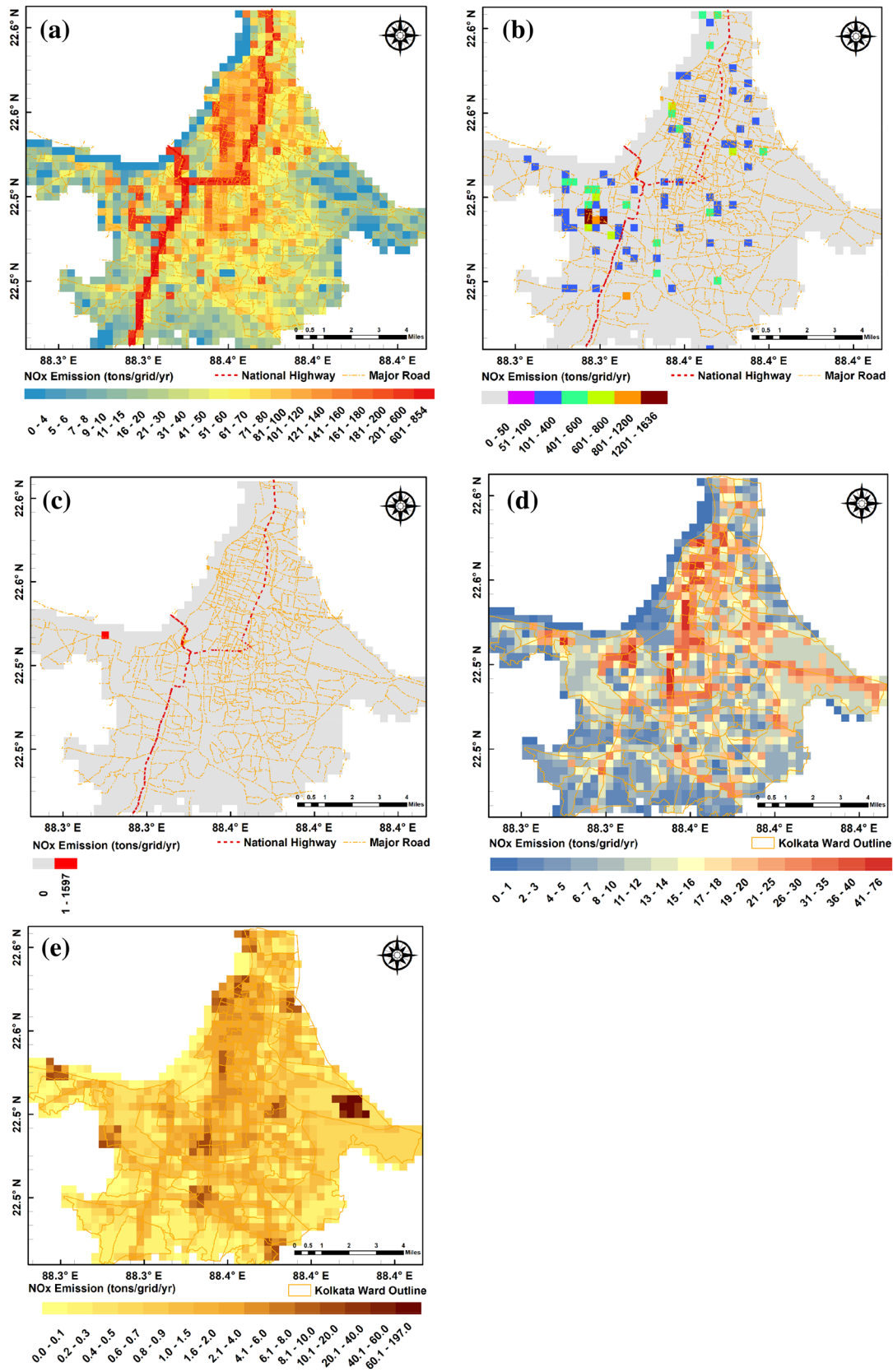


Fig. 6 Sector specific gridded annual NO_x emission from **a** Transport **b** Industry **c** Thermal power plant **d** Residential **e** Other

sector was the largest contributor (~65%) followed by the industrial sector (~21%) as shown in Fig. 5. Diesel generator contributes a sizable fraction (~6%) to total NO_x emission where the diesel combustion in DG sets used in residential complexes for power backup, industrial activity and BTS telecom towers.

As we have categorized all the sources into six major sectors, sector-specific gridded emission was also designed separately as shown in Fig. 6. Transport sector accounts ~84.7 Gg/yr (Fig. 6a), Industrial sector ~27.7 Gg/yr (Fig. 6b); Thermal power plant 1.5 Gg/yr (Fig. 6c), Residential sector with ~14.3 Gg/yr (Fig. 6d) and other sectors with ~2.8 Gg/yr of total NO_x load (Fig. 6e). As the transport sector was found out to be the largest contributor to total NO_x emission, therefore, the gridded spatial pattern of Fig. 6a is discussed. The highest emission load in the order of ~200–854 tons/grid/yr is seen on the national highway. Emission ranging between 80 and 180 tons/grid/yr is found scattered spatially on the major road networks. Rest ~60–80 tons/grid/yr of NO_x emission is well distributed throughout the city. National highways and major roads tend to stay busy as they form the junction to neighbouring states where heavy commercial vehicles and movement of the bus are generally high. The older fraction of the vehicle fleet consisting of HCVs and buses of more than 15 years old contributes to the maximum NO_x emission. In addition, a high population density leads to an increase in vehicular activity. HCV alone contributes ~40% of total NO_x emission from vehicular emissions followed by bus with ~18%. This is especially due to the fact that NO_x has very high EFs for HCV and bus concerning vehicle age. The variation in EFs could cause a change in the relative contribution of NO_x. Similarly, spatial distribution with reference to the rest of the pollutants viz. PM_{2.5}, CO, SO₂, VOC, BC, OC, and relative contribution of several sectors to their total emission is illustrated in Figure S1(a-f) and Figure S2 respectively which can be found in the supplementary file.

3.3 Comparison with past studies

Prior to present study only three studies have been conducted on the emission estimation over Kolkata. However, these studies were done for very older base years and have variable study domains as well as sectors taken into account for emission estimation. Majumdar et al. [27] developed emission inventory for the base year 2015 considering couple of sectors like transport, power, industry, domestic, waste, agriculture, and construction only. Their inventory is just a gross estimation and data collected from secondary sources with no detailed spatial information involved. The gross estimations when is compared to our study shows a difference in the order of two to three

Table 2 Comparison of estimated emission with past studies

Studies considered	Base Year	Air pollutants (Gg/yr)							Study area	Grid Resolution	
		PM _{2.5}	PM ₁₀	CO	NO _x	SO ₂	VOC	BC			OC
Present Study	2020	37.20	61.14	222.62	131.32	60.31	120.45	9.60	16.84	Kolkata megacity	~(0.4 km × 0.4)km
Majumdar et al. [27]	2015	29.40	58.60	78.70	77.90	76.50	35.90	7.70	7.20	Kolkata Metropolitan City (KMC)	NA
CPCB [26]	2011	NA	1.70	21.80	16.10	0.10	NA	NA	NA	Kolkata city	(~2 × ~2) km ²
Srivastava and Majumdar [25]	2004	NA	NA	NA	NA	NA	0.12	NA	NA	Kolkata city	NA

for CO, NO_x, VOC and OC and in the order of one for rest of the pollutants due to accountability of many new sectors and fine activity data. In the same context CPCB [26] conducted a study considering only road transport emissions within the city boundary for the older base year 2011 at 2 km resolution. Most of cases the activity data used to develop an inventory are from secondary sources. Moreover, the targeted pollutants are limited to PM₁₀, CO, NO_x and SO₂ only. The large discrepancy between CPCB and our estimate is due to base year followed by sources taken into account. Similarly, Srivastava and Majumdar [25] focused on an inventory of VOC only for the very oldest base year 2004 that involved few sectors like that of transport, dry cleaning, graphical arts and printing. The VOC emission according to their study was recorded only 0.12 Gg/yr, which is a thousand times less than our estimated VOC emission. Overall, there has been a large disparity between the recorded past and present emission estimations as tabulated in Table 2. These variations are absolutely due to differences in base years and the sources or activity data considered for the studies with corresponding technological emission factors being used. Since the source of emission keeps changing with the growth and evolution of an area, up-gradation of emission inventory becomes most essential. Therefore, our present study has considered all such factors in the most conceivable ways to develop this surface-emission dataset, which is assumed to be most comprehensive, reliable, and better represent the real-time scenario of our area of interest. Moreover, unlike earlier work, present work is the first ever high-resolution gridded estimation that could be useful piece of information for air quality management and air quality modelling.

3.4 Uncertainty in our study

None of the published emissions calculated over Kolkata has carried out the uncertainty estimation for megacity Kolkata. The secondary source of activity data is the biggest concern due to the lack of primary data, which might increase the chances of uncertainties. In our study, we have incorporated data more from secondary sources followed by primary sources like SAFAR campaigns. We have followed the Monte Carlo methodology for a detailed category-wise uncertainty assessment. The factors which are considered for estimating uncertainty in the emission include the (a) Emission factors, (b) Activity data, (c) Proxy data used, (d) Data gaps leading to approximation, (e) Efficiency of control equipment used. Each of these factors was considered for all the sectors. Our targeted sectors were broadly categorized into six major sectors viz. transport, windblown road dust, industry, power plant, residential, and others to easily represent the real

scenario. Uncertainty estimation for the transport sector is complicated due to the use of various aging vehicle categories that have heterogeneous fuel-specific emission factors. Along with that, the proxy data involving the spatial road network across the domain and Ministry of Road Transport and Highways data with the total no. of vehicles running across the city was also considered. The combined uncertainty of emission factors and activity data for the transport sector did not have much disparity due to its source authenticity. The uncertainty estimated for the transport sector was $\pm 34\%$. Wind-blown road dust includes several modulating factors like precipitation, silt load, moisture content, vehicle speed, and weight. These factors were essentially vital factors that modulated the emission. The no. of precipitation days was directly taken from the Indian Meteorological Department's Rain-fall statistics, which barely had errors. The silt load and moisture content depend on climatic factors that have uncertainty $\pm 28\%$ due to its spatial and temporal variability. The weight and speed of the vehicle are directly proportional to the resuspension of the road dust, which is why the combined uncertainty for windblown road dust concerning these factors was $\pm 39\%$. The residential sector included many sub-sectors as discussed earlier which are dependent on the fuel-induced (LPG, fuel wood, kerosene, cow-dung) emission factors and the activity data of per capita consumption. It accounted for the uncertainty of $\pm 41\%$. Similarly, activities associated with the industrial and power plant sector included fuel and technology-specific emission factors. The disparity in availability of fuel and technology-specific activity data was the vital factor that was difficult to ascertain. The spatial locations of the industries and thermal power plants with their corresponding installed capacities were facilitated by the paid confidential source, which smoothened the distribution of emission spatially, however, they accounted for the uncertainty of $\pm 30\%$ individually. The other sector, which comprise several minor sources as mentioned in the activity data section and their associated fuel activities showed an uncertainty of $\pm 31\%$. The gross uncertainty in the whole inventory will be in the range of $\pm 37\%$, which is believed to be in acceptable range. The detailed information on the parameters considered for uncertainty estimation is elaborated in supplementary file.

4 Conclusion

We have identified a wide array of sources that is responsible for deteriorating the air quality of megacity Kolkata. Along with this, certain dominating sources confined to hotspot regions were also identified and discussed. Both

transport and the industrial sector remain the dominating ones. The increase in fleet volume and movement of the aging vehicle fleet are the major reasons for road transport emissions. The propagation of densely condensed small to medium-scale industrial zones is also one of the reasons for elevated industrial emissions. The emerging sector like municipal solid waste burning has become one of the most prominent sources of emission. Regulations on prohibition and banning of uncontrolled open burning of municipal solid waste should be implemented. Easy accessibility and consumption of low-cost solid fuels as the primary fuel for residential and commercial cooking activities in slums make it another responsible emerging sector. Wind-blown road dust can be considered a key source concerning PM_{10} , especially as non-exhaust vehicular emission. Our results throw light on key issues of the megacity proving to be a well-developed reliable high-resolution anthropogenic emission inventory to assess the air pollution issues and assemble required policies for Kolkata. A graded approach with source-specific strategy and control measures must be undertaken to plan actions in order to assess the health impacts and achieve good air quality in Kolkata. Against this background, the measures to mitigate air pollution in Indian megacities are based on skilled scientific knowledge and acute public participation. Concisely, air pollution issues and their associated effects on Indian megacities call for efforts, both from scientific and governmental communities that must walk hand-in-hand to protect the environment and assist the public well-being. This developed emission dataset is part of the SaBe National Emission Inventory for India (SNEIv1.0) dataset for the Air Quality/Climate modeling study.

Few suggestions which would possibly benefit the policy makers:-

- (a) The discard of aging commercial car as well as heavy commercial vehicles from the system followed by fast traffic movement can reduce the transport related emission significantly.
- (b) Flexible office hours will reduce the traffic congestion.
- (c) Slum cooking and construction activities needs to be controlled.
- (d) Silt on the roads should be cleaned periodically.
- (e) Dhapa, the only dumping site in the city should possibly have other alternative approach to treat the waste.

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Author contribution The paper properly credits the meaningful contributions of all the authors involved and all the authors have been actively involved in the substantial work leading to the paper, and will take public responsibility for its content.

Data availability The datasets generated during and/or analyzed during the current study are not publicly available as the information provided is highly classified and is the most sensitive database for air quality management which has extremely limited access. However, the data that support the findings can be made available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Human and animal rights This study does not involve any experiments on human or animal trials and is cruelty free.

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