Aerosol and Air Quality Research

Identification and Quantification of Emission Hotspots of Air Pollutants over Bhubaneswar: A Smart City in Eastern India

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ABSTRACT

Considering the need to identify the sources of air pollution in smart city Bhubaneswar, a non-attainment city in India, a high-resolution comprehensive gridded emission inventory (EI) of eight primary air pollutants has been developed for the base year 2018. The inventory involves detailed activity data with ~0.4 km × ~0.4 km resolution covering the city using a Geographical Information System (GIS) based statistical approach. In total, ~17 major and minor sectors are responsible for the city's air pollution crisis. Windblown road dust, transport sector, and residential cooking activities emerged as the dominating sources. Emissions of CO, NO_x, SO_2, VOC, $PM_{2.5}$, PM_{10}, BC, and OC are estimated to be 112 Gg yr^{-1}, 44 Gg yr^{-1}, 11 Gg yr^{-1}, 73 Gg yr^{-1}, 9 Gg yr^{-1}, 17 Gg yr^{-1}, 5 Gg yr^{-1} and 0.8 Gg yr^{-1} respectively. Nearly 14% and 12% area of the entire study domain are found to be responsible for almost half of PM_{10} and NO_x emissions respectively. The central region of the city with the presence of national highways, major roads, and nearby industrial belts, experiences maximum emission of pollutants. The present gridded surface emission dataset is an essential requirement in framing new mitigation strategies to combat ongoing and future air pollution crises and achieve better air quality.

Keywords: Emission inventory, Air pollution, Anthropogenic emissions, Primary air pollutants

1 INTRODUCTION

Clean and pollution-free air is the primary requirement of all organisms. Urban air quality, under the influence of various pollutants emitted from fossil fuel combustion, biomass burning, industries, construction activities, poor waste management practices, etc., has been deteriorating continuously (Ambade et al., 2021; Beig et al., 2021; Jorquera et al., 2019; Singh et al., 2018). As per HEI (2020), the detrimental effects of these air pollutants resulted in 6.67 million deaths globally and about 980,000 premature deaths in India in 2019. In 2013, the International Agency for Research on Cancer (IARC) classified air pollution as a human carcinogen. Number of fatalities from illnesses caused by pollution exposure is about 5.4 times the number of deaths each year from HIV/AIDS and 8.8 times that from malaria (UNEP, 2021). Besides reducing the life expectancy of a person, air pollution also exacerbates chronic diseases such as asthma, hypertensive disorders, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections (Beig et al., 2013; Chate et al., 2013; Marrapu et al., 2014).

Consequences of air pollution are majorly observed in urban regions due to the enhancement

of socio-economic growth. Being a developing nation, Indian cities are also undergoing the problems of increasing urban settlement, industrial emissions, vehicular traffic, waste burning, etc. As evidence, 22 of the world's 30 most polluted cities are belonging to India and the nation has occupied the third position based on annual average $PM_{2.5}$ concentration (IQAir, 2020). Although cities like Delhi, Mumbai, Bengaluru, and Kolkata are always at the center of attraction regarding poor air quality, the air quality in smart city Bhubaneswar is neither in good terms for which the National Green Tribunal of India has declared the city as one of the non-attainment cities under the National Clean Air Programme (NCAP). Target of the NCAP is to reduce PM levels by 20–30% by 2024, for which identification of sources of pollutants and understanding their corresponding share in the city's total pollution load becomes essential. Level of suspended particulate matter in the city's air has failed to maintain the national ambient air quality standards that were defined by the CPCB. The Air Quality Life Index (Suman, 2019) by Chicago University suggests that life expectancy of residents in Cuttack and Bhubaneswar can be 2.7 years longer if their air quality meets the World Health Organization (WHO) air quality standards.

Although there are a number of studies focusing on the measurement of major air pollutants in Bhubaneswar, none of them represents a detailed emission inventory that highlights the comprehensive listing of sources of air pollutants and their magnitude. Few studies individually focus on concentration of specific pollutants and their relationship with meteorological conditions with the help of backward trajectory and statistical analysis (Mahapatra et al., 2012; Nath et al., 2021; Panda et al., 2021, 2016). A report published by Odisha State Pollution Control Board focused on the ambient air quality status of Odisha from 2006 to 2014. Rout et al. (2012) analyzed the status of ambient air quality in Cuttack and Bhubaneswar. Rout (2018) links land use change with the air quality of Bhubaneswar. Most of these studies have addressed the concentration of air pollutants with meteorological phenomena. However, requirement of spatially resolved high-resolution gridded emission inventory has not been fulfilled yet which would be very essential for designing air-pollution-control measures. Moreover, the unavailability of a gridded surface emission data set limits the air quality modeling study too. Therefore, the initial and foremost step towards mitigation of air pollution begins with a comprehensive study on the identification of both attended and unattended sources and their quantification through an established approach. Accurate quantification of emissions of various pollutants is challenging due to lack of source-specific reliable activity data for Bhubaneswar. Usage of primary data in development of an emission inventory makes it more authentic and reliable but its collection is a tough task and requires financial as well as human resources along with the support of local people.

Hence, an attempt has been made to quantify the emissions of major primary air pollutants from all possible major and minor sources with a high-resolution gridded (~0.4 km × ~0.4 km) emission inventory over smart city Bhubaneswar in Eastern India. The paper is unique in many ways by introducing a detailed surface-emission dataset for the base year 2018 including 17 sectors focusing on eight primary pollutants which are- particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen oxide (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOC), black carbon (BC) and organic carbon (OC). This is the very first ever high-resolution gridded emission inventory for Bhubaneswar that involves activity data from both primary sources by field survey during the pre-pandemic time and secondary sources. The outcomes of the study would play a vital role in planning mitigation strategies and policies for the improvement of air quality by reducing the pollutant load in the city.

2 METHODS

2.1 Study Area

Bhubaneswar, popularly known as the city of temples, is located between 20.27°N and 85.84°E with an average altitude of 58 meters in the Khordha district of Eastern Odisha as shown in Fig. 1. With an area of 186 km^2 and an average population of 1.1 million in 2018, it falls under the jurisdiction of Bhubaneswar Municipal Corporation (BMC, 2022). Being the capital of the state, the city has emerged as one of the fast-growing commercial hubs with administrative, information technology, education, and tourism advantages. As per the national smart cities mission of the
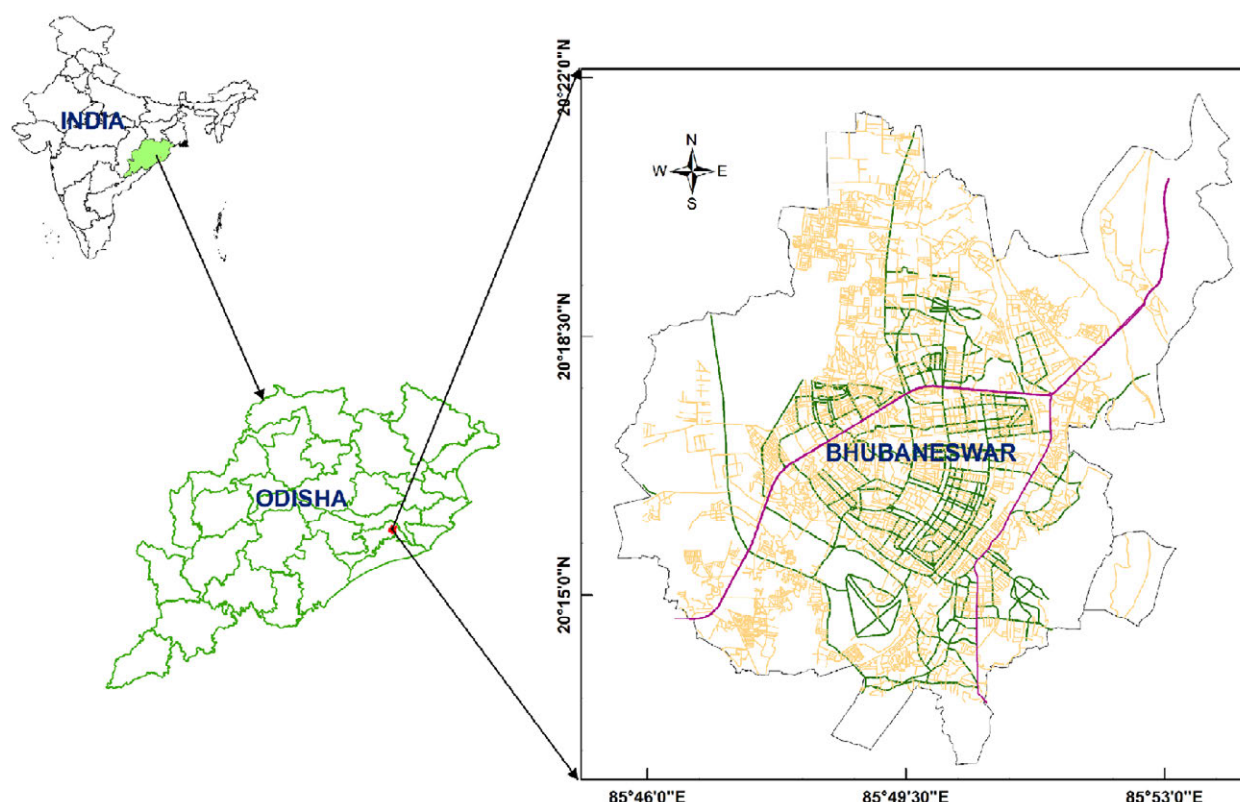
Fig. 1. Area of interest.

Ministry of Housing & Urban Affairs, Govt. of India, smart cities are those where citizens have a decent lifestyle with the availability of smart solutions, core infrastructure, and a clean & sustainable environment. In 2016, Bhubaneswar is chosen to be one of the smart cities and it is the only Indian city among the world's top global smart cities as listed under the Global Smart City Performance Index by Juniper Research (2017). Apart from this, the study area holds a strategic position in India, as most of the polluted air mass from the Indo Gangetic Plains (IGP), and the heavily industrialized Chhota Nagpur Plateau region as well as the western part of India, reaches the Bay of Bengal via this route (Mallik *et al.*, 2019; Sahu *et al.*, 2019).

2.2 Sources of Air Pollution in Bhubaneswar and Activity Data Collection

At present, 17 major and minor sectors have been considered, which are rearranged into five major sectors. Activity data for individual sources have been obtained from primary as well as authentic secondary sources. The objective of primary data collection was to generate unavailable data sets and to improve the accuracy and reliability of inventory by confirming the authenticity of previously available data. More than 20 students from Utkal University were involved to carry out field campaigns from January to May 2018. Primary activity data for sectors like slum, residential, transport and street vendors, etc. are collected along with available secondary data from published official reports and governmental sources. At the same time, the assembled primary data are checked for quality before incorporating them for emission estimation. Sector-specific collected primary and secondary datasets along with their sources are presented in Table S1.

2.2.1 Road transport

Parameters used to estimate the emissions from transport sector are presented in Table 1, which includes number of vehicles, fuel type, and Vehicle Kilometres Travelled (VKT) per day with respect to vehicle category. A mounting dependence on the usage of private vehicles has been observed, as nearly half of all households in the city own two-wheelers and 11% own cars (OLA Mobility Institute, 2018). In the present study, the whole road transport system is broadly classified

Table 1. Fuel type, Number of registered vehicles and VKT details of each vehicle category.

SL. No.	Category	Fuel Type	Number of Vehicles	VKT/Day (km day^{-1})
1	2W	Petrol	813668	45
2	3W	CNG/ Diesel	86581	150
3	Buses	Diesel	13155	180
4	Personal Cars	Petrol	406349	120
5	Commercial Cars	Diesel	45150	270
6	HCV	Diesel	27189	60
7	LCV	Diesel	56519	120
8	MSLV	Diesel	14129	50
Total			1462741	

into eight categories of vehicles, which are Two-wheelers (2W), Three-wheelers (3W), Buses, Personal Cars (P Car), Commercial Cars (C Car), Heavy Commercial Vehicles (HCV), Light Commercial Vehicles (LCV), and Multi-utility vehicles (MSLV). Percentage contribution of different vehicles is illustrated in Fig. 2(b). From registered vehicle data analysis, it is found that around 15% of vehicles are older than 15 years and emit high amounts of pollutants. In 2018, Bharat Stage-IV norms were made mandatory by Govt. of India to regulate the emissions of air pollutants released from motor vehicles. As per this rule, the emission standard of pollutants with respect to each vehicle category was set and the Worldwide Harmonized Motorcycle Test Cycle (WMTC) was made compulsory for vehicles registered after 2017 (ICCT, 2014). Despite this, a number of older vehicles registered before this period are still moving on roads even after the phasing-out procedure. Since driving pattern of each vehicle category varies significantly with urban conditions, hence kilometre travelled by individual vehicle category also plays an effective role to determine pollution load linked to vehicular exhaust. Therefore, vehicle kilometres travelled per day (VKT day^{-1}) as well as fuel type were adopted from the primary data collected during field campaigns held in Bhubaneswar.

During the transport survey, vehicle density and types of vehicles at various traffic junctions and busy roads across the city have been counted using click counter devices for 30 days, which includes both weekday and weekend scenarios. During survey, 33 locations on major roadways were taken for vehicle counting across the city, illustrated in Fig. 2(c). The survey locations were chosen based on road types, road congestion due to vehicular density, major busy routes to various marketplaces, educational institutions, temples, hospitals, hotels, and residential areas etc. Fig. 2(a) represents the vehicle density over these roads of Bhubaneswar. Nakhara Square, which connects Bhubaneswar and its twin city Cuttack, experiences maximum vehicular density. In addition to this, some other busy roads due to the presence of major offices, schools, railway stations, shopping malls, and temples in nearby regions include Acharya Vihar road, Jaydev Vihar road, Fortune tower road, RMRC road, Patia road, Ram Mandir road, etc.

2.2.2 Wind-blown road dust

Although Bhubaneswar is a planned city, the dust load on both major and minor roads is high due to a lack of proper maintenance that aggravates dust resuspension due to vehicular movements. In addition to that, most two-wheelers prefer to drive on unpaved shoulders of the roads, especially during traffic hours. Based on digitization of the existing road networks, the city has a total road length of ~1170 km, which includes ~904 km of minor roads, ~214 km of major roads, and ~52 km of national and state highways. However, conditions of the roads are down-and-out, due to which re-suspended dust from both paved and unpaved roads, driven by increasing vehicular movement, holds a major share of PM concentration in the air. Lack of proper maintenance and ongoing road and over-bridge constructions along the roads of Mancheswar, Old town, Kapila Prasad, Khandagiri, etc., have been experiencing high dust loads. Moreover, vehicle-induced road dust is directly proportional to the density of vehicles plying, their average weight, and mean speed. Besides that, amount of silt load on roads, average precipitation days, soil moisture content, etc., also act as modulating factors. All these factors used to estimate the emission load, are briefly tabulated in Table S1.
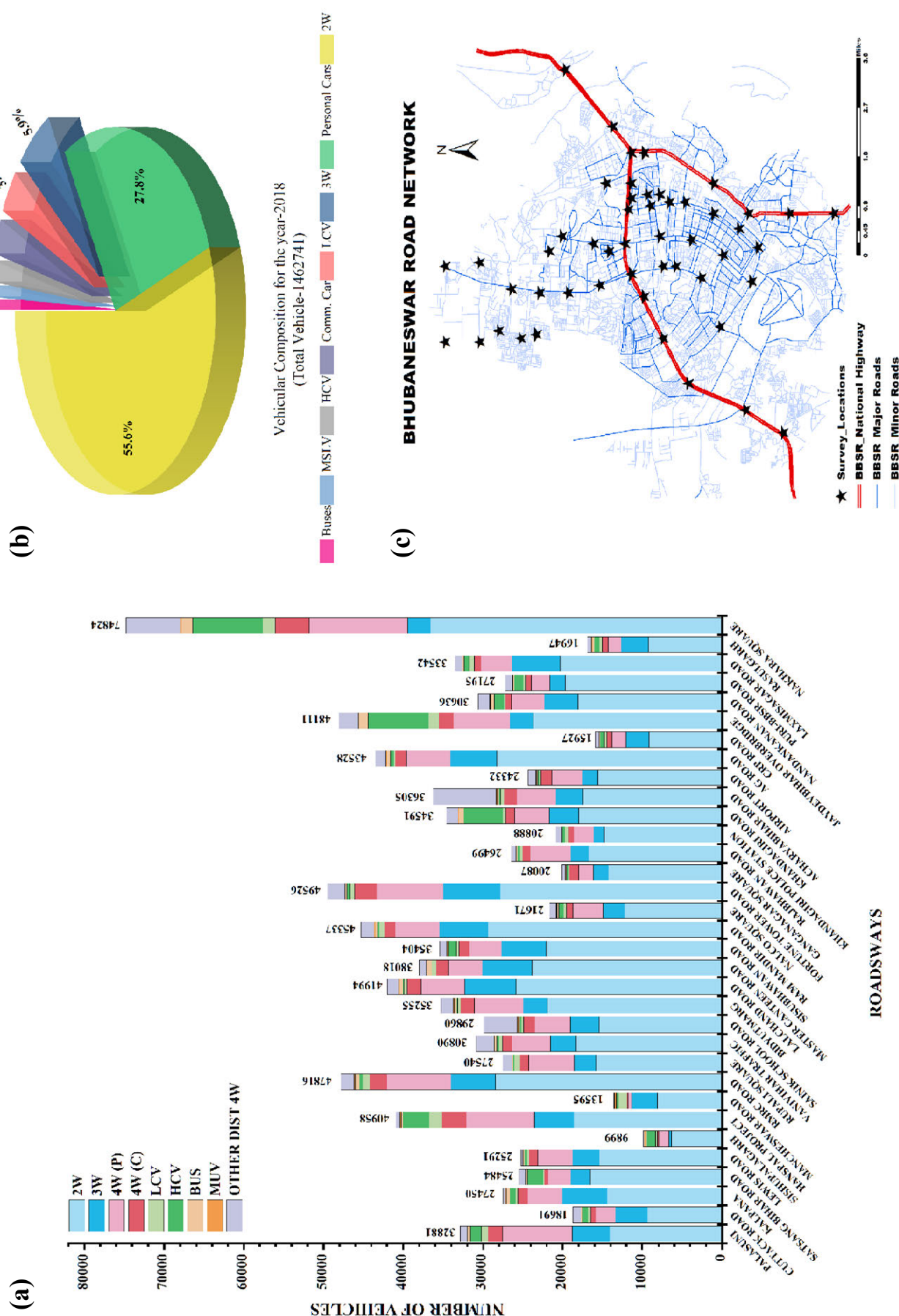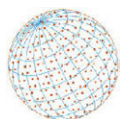
Fig. 2. (a) Vehicle density over major roads, (b) Vehicular composition and (c) Survey locations.

2.2.3 Industry

Bhubaneswar has become one of the fast-growing, major trading and commercial hub in Odisha and Eastern India. As per the report of the ministry of Micro, Small & Medium Enterprises (MSME, 2022), 2019–20, there are 21,546 registered industrial units in the Khordha district. According to the CCIPL (2006), there are about 88 industries comprising three large-scale, 34 medium scale and 51 small-scale industrial units operating majorly in the four industrial estates of Bhubaneswar namely Rasulgarh, Mancheswar, Chandaka Nuclear Industrial Complex (CNIC), Bhagabanpur and other regions. Industrial sector in the city includes steel, paper, automobile, pharma, food, electronics industries, and others. Most of the small-scale industries operating inside the city fall under unorganized sectors that do not have necessary pollution control measures and with a pollution impact potential of a 2–5 km radius. Fuel usage pattern in the industries is highly uncertain because of the unavailability of a systematic database for fuel used by individual industries, so the fuel consumption pattern is adopted according to the national average. The domain selected for the study does not include any thermal power plants hence this sector has not been considered for emission estimation.

2.2.4 Residential

Emissions from households, Slums, Street Vendors, and Diesel Generators have been included in this sector. The sub-sector 'Household' represents emission of various pollutants from cooking activities of urban population. According to the reports of census India, population of the city was ~8 lakh in 2011 with an average of 2.53% increase per year (India Census, 2011; Population Census, 2011). Hence, the total population of Bhubaneswar is ~1.1 million with a 3% increase from 2017 (UN DESA, 2019). Since 1/3rd of the total population resides in slum areas (CCIPL, 2006), rest of the urban population was found to be ~7 lakhs with an average household size of four per family. On the other hand, a slum represents a poorly built congested area having a minimum of 300 population or about 60 to 70 households in unhygienic surroundings, usually with inadequate infrastructure that lacks proper sanitary and drinking water facilities (Rout, 2008). Approx. 835 households and 537 slums were surveyed in major residential areas of Bhubaneswar including Sahid Nagar, Kharavel Nagar, Chandrasekharpur, Patia, Nayapalli, Khandagiri, Salia Sahi, Dumduma Bhoi Sahi, Sriram Nagar, Behera Sahi, Nilachakra Nagar, etc. A structured schedule was prepared to interrogate the head of each selected household for enquiring about the type and quantity of fuel they use for cooking activities.

Cooking activities of roadside eateries, dhabas, fast food stalls, hotels, restaurants, and other street vendors also hold a significant share in contributing to urban air pollution. Because of the increasing demand and a sustainable source of income, people in urban areas especially the poor and slum dwellers have been opting more towards street vending. According to the president of the All Odisha Roadside Vendors' Association, there are more than 22,000 vendors across the city (Kumar, 2012). It has been assumed that nearly 60% of the total vendors earn their livelihood by selling different fast foods and being involved in other cooking-related activities. During the field survey, activity data from 980 street vendors, hotels, and restaurants were collected. The type and quantity of cooking fuel, opening hours and peak seasons of business, type of oil used and cooking duration, etc. were thoroughly observed and enquired from the vendors. Information obtained from the field survey regarding the cooking activities practised by slums and other households, hotels, and street vendors of the city has been given in Table 2. The collected values are crosschecked with other studies (Das and Pal, 2019; Dash, 2015).

Apart from the cooking activities, this sector also addresses emissions from diesel generators (DG) which are used as a power backup in many shopping malls, restaurants, hotels, hospitals, theatres, residential complexes, etc. Considering the lifestyles of the city's population, it has been assumed that at least 10% of urban households use DG sets as a backup plan. Each year ~9000–12000 liters of diesel is consumed by a standardized 12–25 kWh diesel generator used in telecom towers (Sahu et al., 2015). In the city, the DG sets run at least for an hour per day.

2.2.5 Others

The other sector comprises sub-sectors like aviation, open waste burning, construction dust, incense sticks, mosquito coils, cigarettes, and crematoriums. Emission from 'aviation' is calculated
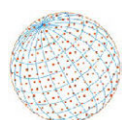
Table 2. Fuel type & quantity used per month by households, slum and street vendors.

Sub-sectors	Sample Collected	Types of fuel used	Avg. quantity of fuel used per month (in kg)	Percentage of total population using the fuel (%)
Household (Urban Population)	835	LPG	14.5	76
		Wood	75	11
		Cow dung	120	7
		Kerosene	8	3
		Coal	45	3
Slum	537	LPG	14.5	39
		Wood	75	31
		Cow dung	120	12
		Kerosene	8	7
		Coal	45	11
Hotels & Street Vendors	980	LPG	29	27
		Wood	300	37
		Coal	250	32
		Kerosene	30	4

based on Air Traffic Movements (ATM). The only international airport of Odisha that is the Biju Patnaik International Airport (BPIA) is located just 3 km away from Bhubaneswar city Centre. Due to a significant number of national and international events including the Men's Hockey World Cup organized in Bhubaneswar, the BPIA achieved a whopping four million annual passenger traffic in the fiscal year 2018–19. As per the BMC portal, the city generates approx. ~520 tons of solid waste per day. The collected Municipal Solid Wastes (MSW) from various parts of the city are transferred to the Temporary Transfer Station (TTS) near Sainik School. Later, these wastes are transported to the dumpsite located at Bhuasuni in Daruthenga every year (Times of India, 2019). Since this area remains outside the study domain, emission from dumpsites has not been considered for the city. According to the CPCB (2019), 2018–19, there is no Waste to Energy (WTE) plant in Odisha.

With rapid urbanization and numerous construction activities like roads, flyovers, apartments, multi-complexes, building blocks, etc., Bhubaneswar has been experiencing a bulk amount of suspended dust from construction activities. Transfer of construction materials and debris released from land clearing and demolition through multi-utility vehicles like trucks, tractors, bulldozers, scrapers, compactors, etc., increase the amount of dust load in air. Maximum numbers of brick kilns are located outside the selected city domain, hence emission from brick industries has not been considered for our study. Emissions from the crematory grounds hold a major share in polluting the air, especially in the local areas. Although many cities are opting towards an electrical cremation system, the traditional Hindu funeral pyre system that is burning dead bodies is still effective in Bhubaneswar. There are at least 15–20 crematorium grounds in Bhubaneswar where traditional burning is preferred. Bhubaneswar, famous as the city of temples, has around 700 temples located all over the city, specifically in the old town region. Apart from that, major population uses incense sticks and diyas as a traditional approach. Besides households, street vendors also use incense sticks to worship at the time of opening their business every day. Use of mosquito coils by households particularly by slum dwellers is another emitter of indoor air pollution. Usage of these coils increases in rainy seasons due to the breeding of mosquitoes in unhygienic water logging conditions. Similarly, smoking tobacco and cigarettes also remains a source of pollutants. The chemical composition of incense sticks, mosquito coils, and tobacco has been collected from previous studies (Cohen *et al.*, 2013; Kumar *et al.*, 2014). Fig. 3 demonstrates the spatial location of the major emission sources over Bhubaneswar.

2.3 Methodology Used

For developing the emission inventory, a "bottom-up" approach has been adopted over the widely used "top-down" approach in order to improve the accuracy, reliability, and uncertainty of
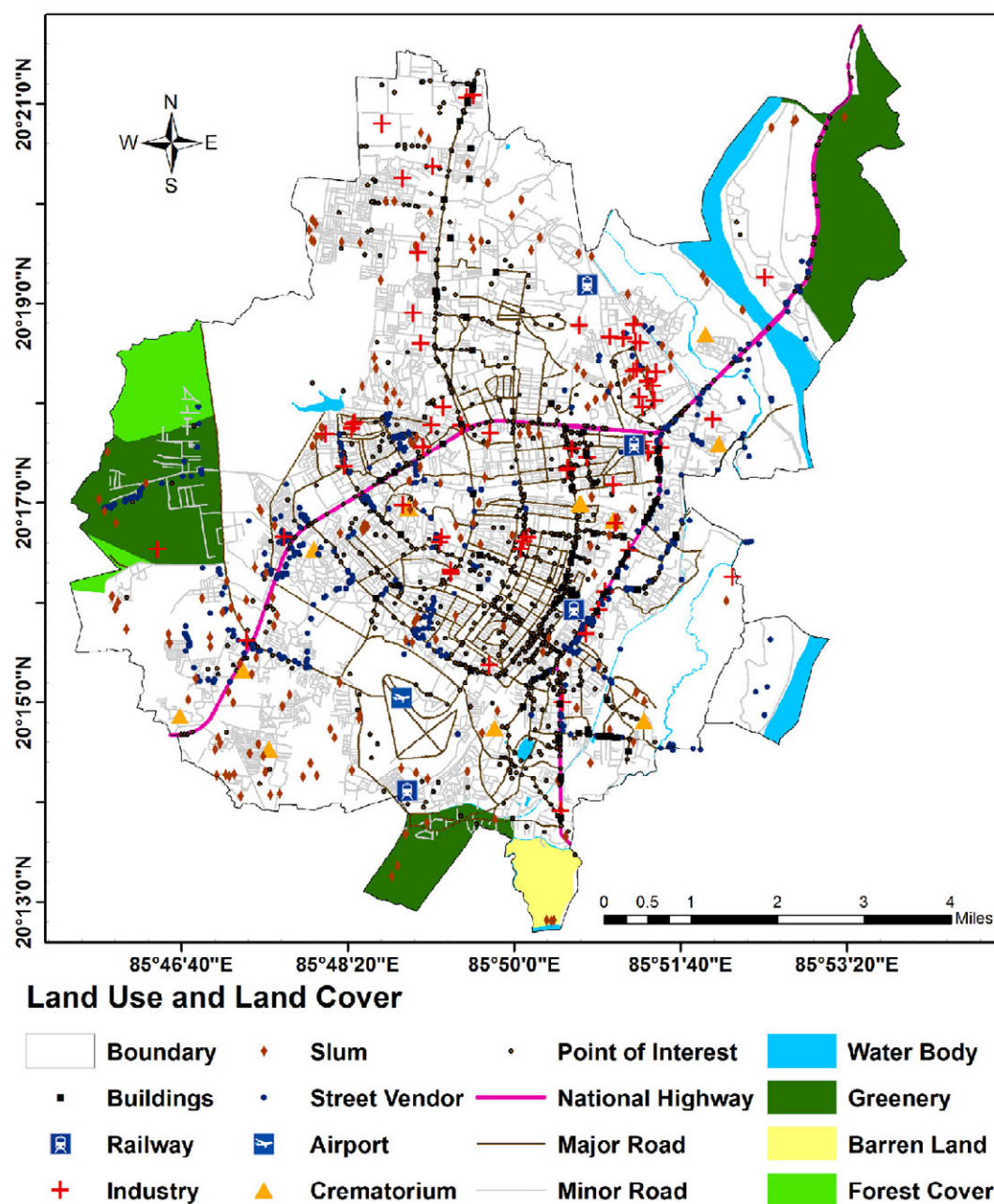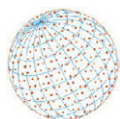
Fig. 3. Spatial locations of different emission sources with land use and land cover.

inventory. The accuracy of emission estimated depends on two major components i.e., Emission Factor (EF) and activity data. Activity data used in this study has been generated during the field survey. EF is the representative value of a pollutant released into the atmosphere with an activity associated with release of that pollutant. EF varies for each sector depending upon the mode of combustion, fuel type and chemical composition, usage pattern, emission control device, etc. Apart from this, EFs also differ from region to region because of the different meteorological parameters and climatic conditions. These experiment-based values are taken from several research articles and reports keeping the Indian city scenario in mind and have been listed in our recent studies (Mangaraj *et al.*, 2022a, 2022b). For estimating vehicular emission, EF developed by the Automotive Research Association of India (ARAI) and the value published by our previous studies (Sahu *et al.*, 2020, 2021a, 2021b), have been used. The equations used to estimate the emission are similar to that adopted by Klimont *et al.* (2002), and in our previous works (Sahu *et al.*, 2011, 2014, 2021b).

Eq. (1) represents the generalized formula, which is used for estimating emissions from all other sources except the sectors like road transport and wind-blown road dust. Emissions from road transport are estimated as per Eq. (2) due to technology-specific vehicular emission factors derived by ARAI (2007) and CPCB (2010). Since the sector wind-blown road dust considers some important modulating factors; hence, Eqs. (3–4) are used for estimating emissions due to vehicular movement on paved and unpaved roads respectively.

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

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

$$T_c = \sum (V_l \times D_l) \times Ef \tag{2}$$

where, T_c = Total Emission; V_l = Category-wise vehicle number; D_l = Distance traveled by each vehicle type (VKT year^{-1}); Ef = Fuel and vehicle type specific emission factors.

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

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^{-1}); st = silt load on the road surface (g m^{-2}); 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.

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

where, T_{up} = size-specific EF (lb VMT^{-1}); 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 estimation, the emission is distributed spatially over the selected area of interest using the tools from Geographic Information System (GIS). For gridding of the emission values with respect to our required resolution, different proxies have been incorporated to improve the fine spatial resolution. Layers of road networks including state and national highways, and minor and major roads have been created for the distribution of emissions from re-suspended road dust and the transport sector. For residential sectors, region-specific population density, urban spread of the grid, and for other sectors, major points of interest like the locations of market complexes, hospitals, hotels, street vendors, temples, residential blocks, and commercial zones are used as a proxy to spatially assess the emissions. Emissions from industries are allocated to the specific grids where the major industrial clusters are present. Comprehensively, Bhubaneswar city's geographical region is covered by 848 grid cells, each having a resolution of ~0.4 km × ~0.4 km.

3 RESULTS AND DISCUSSION

In the present study, emission inventories of gaseous pollutants such as CO, NO$_x$, SO$_2$, and VOC as well as particulate matter PM$_{2.5}$, PM$_{10}$, BC, and OC have been developed at a fine resolution of (0.4 km × 0.4 km), which incorporated all possible major/minor sources over Bhubaneswar in 2018. The estimations for CO, NO$_x$, SO$_2$, VOC, PM$_{2.5}$, PM$_{10}$, BC, and OC are found to be 111.58 Gg yr^{-1}, 44.41 Gg yr^{-1}, 10.58 Gg yr^{-1}, 72.84 Gg yr^{-1}, 8.89 Gg yr^{-1}, 16.51 Gg yr^{-1}, 4.61 Gg yr^{-1} and 0.83 Gg yr^{-1}
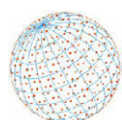
Table 3. Sector-specific annual emissions (in Gg yr^{-1}) for Bhubaneswar.

Sector	PM$_{2.5}$	PM$_{10}$	CO	NO$_x$	VOC	SO$_2$	BC	OC
Windblown-Road Dust	0.561	5.149	NA	NA	NA	NA	NA	NA
Transport	4.655	4.750	98.473	36.284	72.579	6.896	3.874	NA
Industry	0.551	0.876	0.300	2.248	NA	2.867	0.135	NA
Household	0.393	0.550	3.027	0.367	0.025	0.069	0.031	0.239
Slum	0.304	0.404	2.381	0.273	0.017	0.059	0.024	0.183
Street Vendor	0.344	0.995	4.464	0.567	0.025	0.335	0.065	0.363
Diesel Generator	0.915	1.144	0.516	2.390	NA	0.159	0.468	NA
Aviation	NA	NA	1.192	2.198	0.193	0.176	NA	NA
Construction	0.95	2.367	NA	NA	NA	NA	NA	NA
Incense Sticks/Mosquito Coils/Cigarettes	0.187	0.227	0.853	0.040	0.003	0.026	0.011	0.020
Crematory	0.040	0.050	0.380	0.046	0.002	0.001	0.004	0.026
Total	8.897	16.513	111.586	44.414	72.845	10.588	4.613	0.831

respectively. Since this is the first-ever developed emission inventory for Bhubaneswar, no comparison with previous studies has been done. The pollutant-specific share of different sub-sectors is provided in Table 3.

3.1 Spatial Distribution and Sectoral Contribution

After a brief analysis, it is found that emission distribution of the above eight pollutants is more or less equivalent because of the similar emitting sources. Because of space limitation, spatial distribution of one particulate pollutant (i.e., PM$_{10}$) and one gaseous pollutant (i.e., NO$_x$) have been elaborated here focusing on their source in a comprehensive manner.

3.1.1 Particulate pollutant (PM$_{10}$)

Fig. 4(a) illustrates the spatial distribution of total PM$_{10}$ emission (17.3 Gg yr^{-1}) and its relative contribution from all sectors. Maximum PM$_{10}$ emission was found to range between 100–157 tons grid^{-1} yr^{-1}, which is prominent over the areas having national highways and major traffic roads. On the other hand, the least emission having a range of 10–30 tons grid^{-1} yr^{-1} is spatially scattered along the peripheral zones of Bhubaneswar that have minimum urban settlement and less vehicular movement due to presence of the Chandaka forest and many rivers like the Daya, the Kuakhai, etc. It is observed that 50% of PM$_{10}$ comes from only ~14% area of Bhubaneswar. Some of the PM$_{10}$ hotspots are confined over areas like Rasulgarh, Unit-9, Unit-3, Laxmisagar, Unit-4, Gajapati Nagar, Nayapalli, Khandagiri, Mancheswar, Patia, and Chandrasekhar, etc., which were precisely demonstrated in Fig. 5. The grid having the maximum emission of ~157 tons grid^{-1} yr^{-1} is located in the Eastern region of the city i.e., Rasulgarh area. Major contribution to PM$_{10}$ in this area comes from the transport sector. With the presence of the Kolkata-Chennai National Highway and Cuttack-Puri by-pass junction, Rasulgarh becomes one of the busiest roads in the city. In addition to that, the area is an inlet towards Bhubaneswar hence, many other district vehicles along with passenger buses travel across this area. The second highest PM$_{10}$ emission peak is observed at Bhoinagar, Unit-9 with ~130 tons grid^{-1} yr^{-1} that majorly comes from resuspended road dust followed by vehicular emissions. Unpaved shoulders of roads in this area and heavy traffic rush contribute to the emission of PM$_{10}$. Kharvela Nagar, Unit-3 occupies the third position among the hotspots with ~128.4 tons grid^{-1} yr^{-1} of PM$_{10}$ emissions in which road dust and residential cooking activities play the dominant role. Being nearby to the railway station, Mo Bus stand, and major offices, the road experiences a large number of vehicular activities even at the odd time of the day. In addition to that, selling food items and cooking activities of many roadside street vendors emit PM$_{10}$ in this area. The region with a large number of roadside dhabas, street vendors, and fast-food stalls is found to be the Laxmisagar region with an approx. emission of ~128.2 tons grid^{-1} yr^{-1}. Usage of large amounts of coal and wood as cooking fuel especially by the food vendors makes the area a dominant source of PM$_{10}$ from the residential sector. Patia region also has the residential sector as the highest emitter of PM$_{10}$ because of the usage of solid fuels in cooking activities of many hotels,
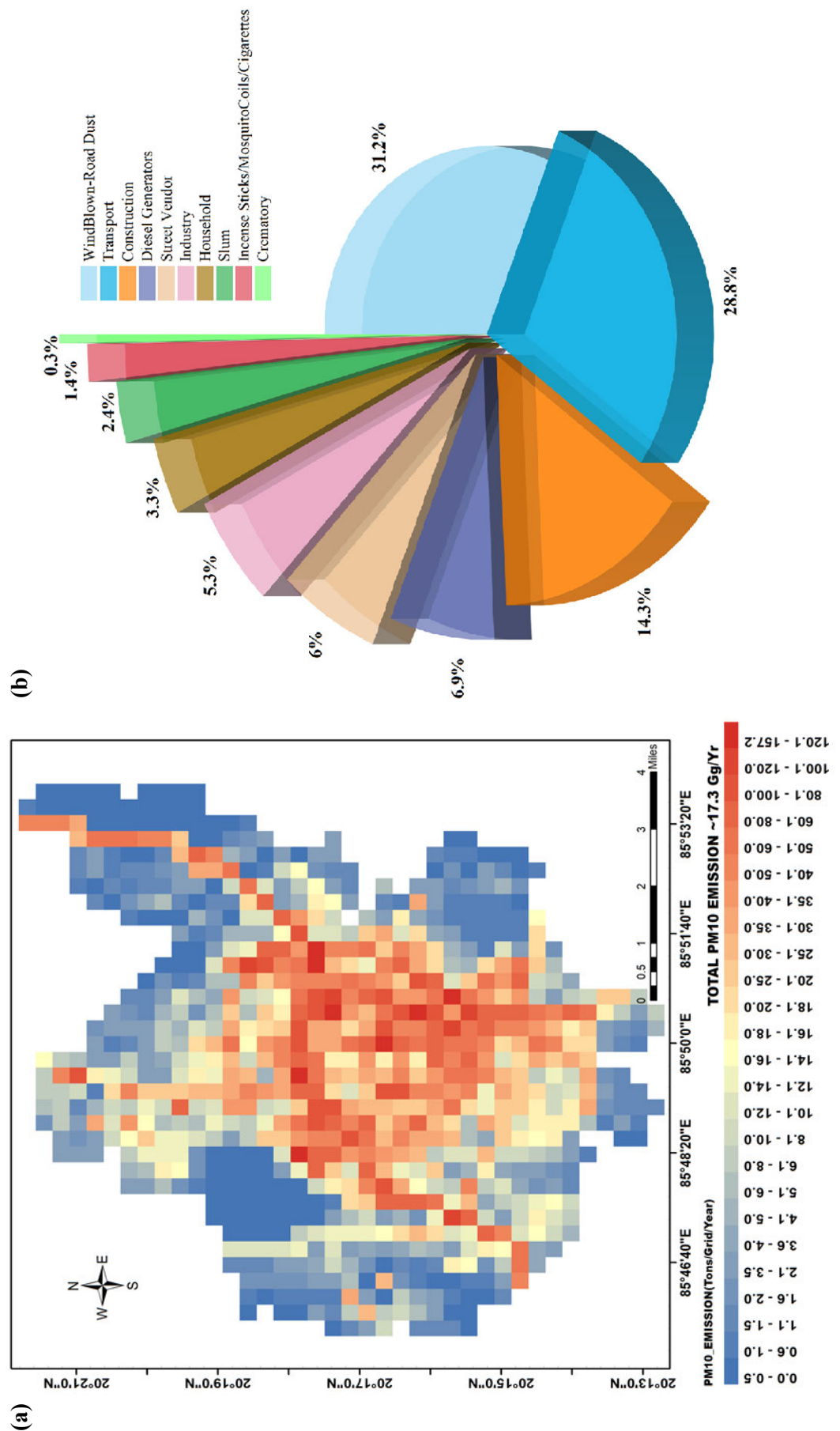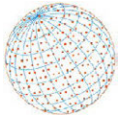
Fig. 4. (a) Gridded annual PM$_{10}$ emissions, (b) PM$_{10}$ contribution from major and minor sectors.

1. Rasulgarh
2. Unit-9
3. Kharvela Nagar
4. Laxmisagar
5. Unit-4
6. Gajapati Nagar
7. IRC Village, Nayapalli
8. Khandagiri
9. Mancheswar
10. Patia

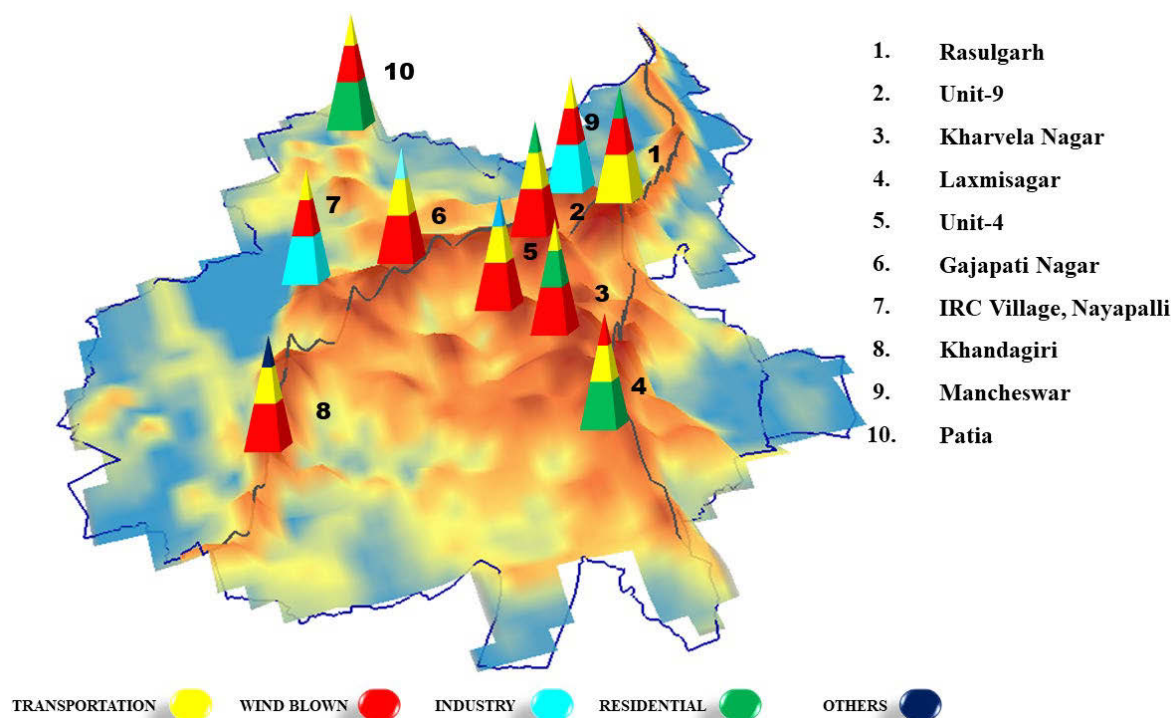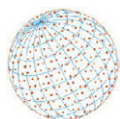TRANSPORTATION   WIND BLOWN   INDUSTRY   RESIDENTIAL   OTHERS

Fig. 5. PM_{10} emissions and their sectoral contribution.

street vendors, and slum dwellers of Prasanti Vihar, Damana Hata Basti, Patia Jali Munda Sahi, CS Pur Sabar Sahi, Sikharchandi clusters, etc. Other slum pockets of Bhubaneswar such as Salia Sahi, Dum Duma, Khandagiri, and BDA colony also contribute to PM_{10} emissions of ~120 tons grid^{-1} yr^{-1} through their domestic cooking practices and biomass burning. The area of Nayapalli and Mancheswar having many unorganized small industrial clusters and high vehicular movements tend to contribute a significant load of PM_{10} (~120 tons grid^{-1} yr^{-1}). A large number of HCVs and LCVs carrying raw materials and industrial goods over the unpaved roads of these areas particularly of Mancheswar Industrial estates increase wind-blown dust events in an impactful manner. Average weight of heavy and light commercial vehicles used to carry heavy goods in poor road conditions triggers vehicular exhaust emission. Apart from that, major roads like Vani Vihar road, Ashok Nagar Road, Unit-4 road, Gajapati Nagar, Khandagiri road, Chandrasekharpur road, and Nayapalli road also carry a significant load of PM_{10} (~100–122 tons grid^{-1} yr^{-1}) because of the high volume of traffic and suspended road dust. The sector-specific PM_{10} contribution is plotted in Fig. 4(b).

The gridded PM_{10} emission from major sectors was plotted separately in Fig. 6, from which the emission distribution could be recognized spatially. The five major sectors considered here are-transport sector which contributes ~4.7 Gg yr^{-1} as illustrated in Fig. 6(a), re-suspended road dust ~5.1 Gg yr^{-1} (Fig. 6(b)), industries ~0.8 Gg yr^{-1} (Fig. 6(c)), the residential sector with ~4 Gg yr^{-1} (Fig. 6(d)) and the other sector with ~3.4 Gg yr^{-1} of PM_{10} load (Fig. 6(e)). Current study indicates that wind-blown road dust contributes to maximum PM_{10} emission due to high silt loading along major roads. Fig. 6(b) illustrates that the national highways and major roads bear PM_{10} emissions with the range from ~20–45 tons grid^{-1} yr^{-1}. Roads having heavy traffic congestion include Vani Vihar road, Rasulgarh Square, Acharya Vihar road, Kharabela Nagar road, Kalpana square, etc. Heavy traffic congestion by commercial vehicles contributes ~28% to total PM_{10} emissions. Therefore, it can be said that slow-moving traffic along with road condition triggers emission load and cause degradation of urban air quality.

3.1.2 Gaseous pollutant (NO_x)

Spatial distribution of total NO_x emission (44.4 Gg yr^{-1}) and its relative contribution from all sectors in Bhubaneswar has been shown in Fig. 7. Since vehicular exhaust contributes a major amount of NO_x, the central region of the city shows the maximum NO_x emission in the range of
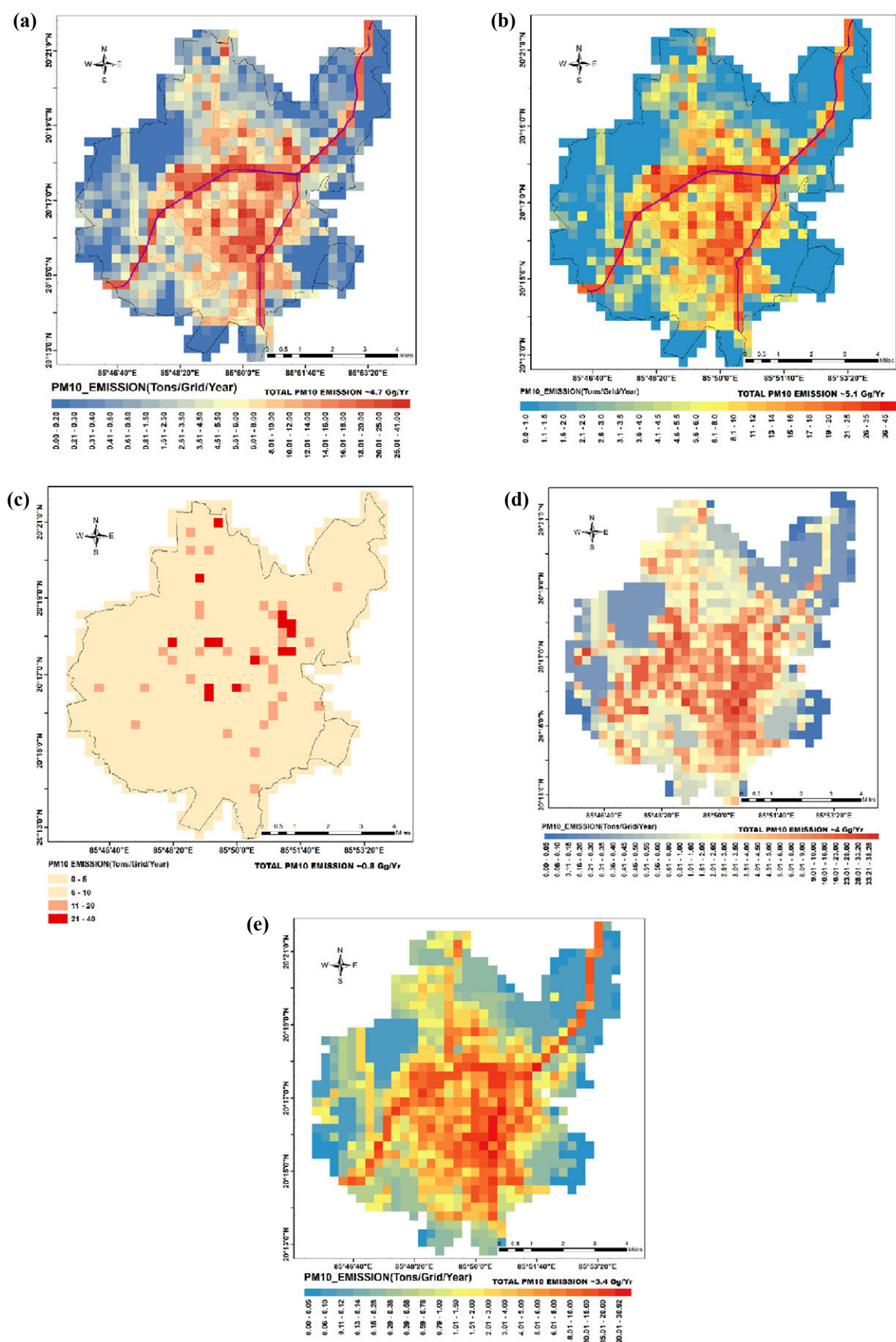
Fig. 6. PM$_{10}$ emissions from (a) Transport, (b) Wind-blown road dust, (c) Industry, (d) Residential, and (e) Other sectors.
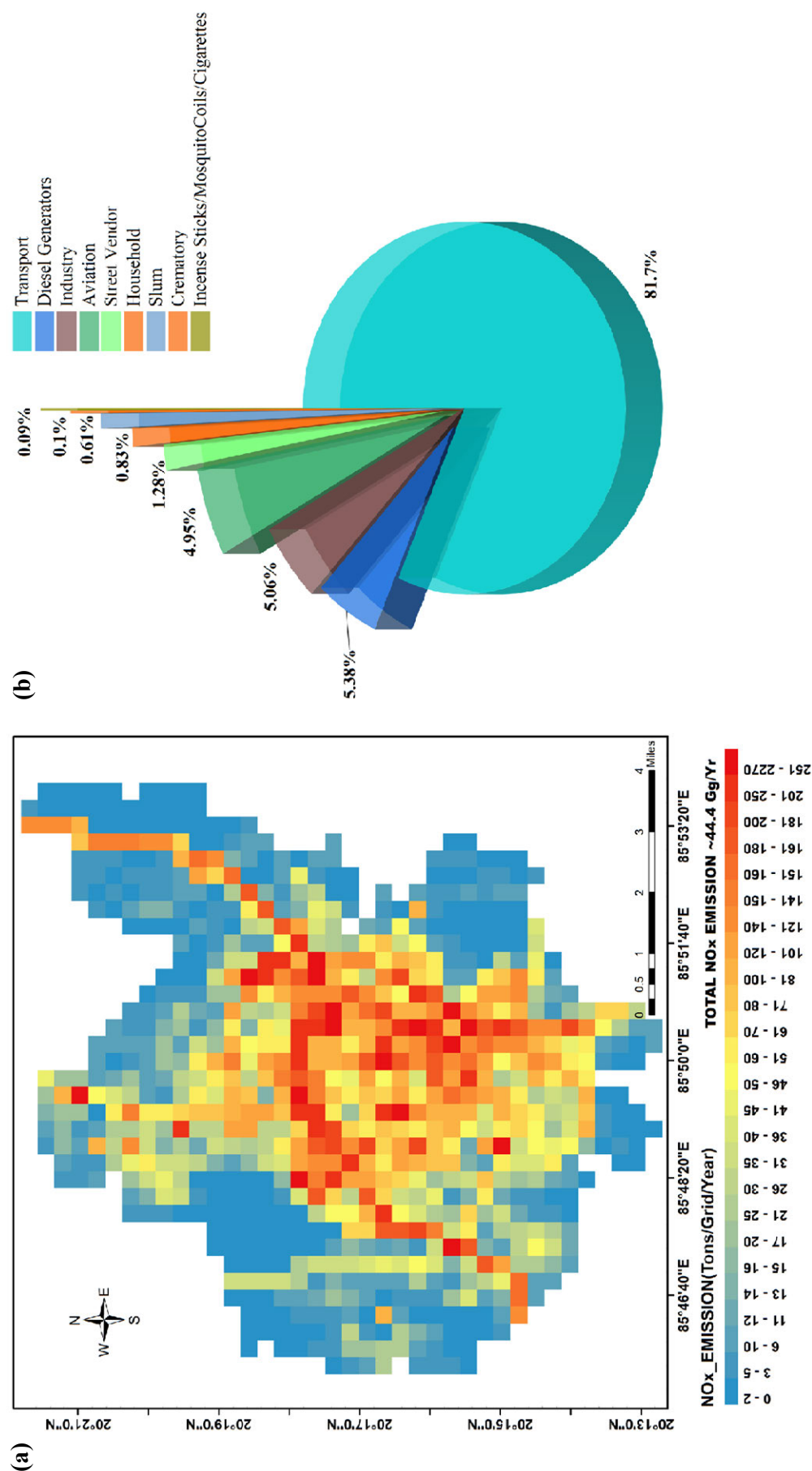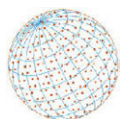
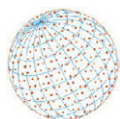**Fig. 7.** (a) Gridded annual NO$_x$ emissions, (b) NO$_x$ contribution from major and minor sectors.

~160–2270 tons grid^{-1} yr^{-1} due to the presence of dense road network including national highways and major roads. Total emission of NO$_x$ from the transport sector is ~36 Gg yr^{-1}, which is the highest among all the sectors. The areas including Airport road, Rasulgarh, Mancheswar, Unit-3, Unit-9, Gajapati Nagar, Unit-4, Khandagiri, Laxmisagar, Kalpana Square, Patia and Chandrasekharpur with a large number of vehicular activities become the dominant contributors of NO$_x$ with ~0.3–2 Gg yr^{-1} emission. As aviation sector holds a significant share of NO$_x$ emissions (Freeman *et al.*, 2018), so one of the hotspots is also found to be at the airport road. Industrial emission is the second highest contributor of NO$_x$ with an average emission of ~2 Gg yr^{-1}. Therefore, the eastern region of the city including Rasulgarh and Mancheswar area is found to be among the high emitters of NO$_x$ due to the presence of many medium and small-scale industries. Residential sector including cooking activities by the slum localities, street vendors, etc., and the emission from diesel generators together contribute ~3.5 Gg yr^{-1} to the total NO$_x$ emission. Surprisingly, it has been observed that only 12% of the grid holds a share of 50% of NO$_x$ emissions in the city. The sector-specific NO$_x$ contribution is demonstrated in Fig. 7(b), which shows that transport is the highest contributor (~81%) to total NO$_x$. With high vehicular movements of personalized and aging vehicles specifically two-wheelers and cars, this sector remains the dominating one. Since the combustion of diesel emits more amount of NO$_x$ (Sahu *et al.*, 2012), the emission from diesel generators stands as the second highest contributor with ~5.3% of total NO$_x$ emission.

3.2 Uncertainty

In our study, we have incorporated data from primary sources followed by secondary sources. Data collected from the local people varies from person to person. At the time of inquiry, they usually do not give accurate data either knowingly or unknowingly. Although secondary sources of activity data are collected from authentic government sites, city-specific data might remain uncertain up to a few extents. Here, we have followed the Monte Carlo error propagation simulation and mean deviation method for detailed category-wise uncertainty estimation (Paliwal *et al.*, 2016). The factors like (a) Emission factors, (b) Activity data, (c) Proxy information, (d) approximated data gaps, (e) Efficiency of controlling equipment, etc. has been considered for uncertainty estimation of all the sectors. Due to space constraints, it is difficult to put forth the whole analysis process for all sectors. Therefore, we have mentioned sector-wise uncertainty percentage. The uncertainty calculated for the transport sector is ± 30%. This estimated value greatly depends upon the use of different sector-specific emission factors and activity data including different road networks along with the total number of vehicles. Due to the source authenticity, the gross uncertainty of emission factors and activity data did not have much disparity. Crucial factors like precipitation days, moisture content of the soil, silt load, speed, and weight of vehicles have been considered for emission calculation from the Wind-blown road dust sector. Number of precipitation days in 2018 was taken from the Rainfall statistics of IMD (2020), which is not likely to have errors but climatic factors can influence the silt load and moisture content of the soil. Therefore, this sector has an uncertainty of ± 30%. The residential sector involving cooking activities, and diesel generator emissions have fuel-induced (LPG, wood, kerosene, Diesel) EFs, and activity data of per capita fuel consumption accounted to have ± 32% uncertainty. The industrial sector also uses fuel and technology-specific emission factors. However, activity data used for this sector remains disparity because of the unavailability of accurate data like usage of types and amount of fuel, controlling equipment, technologies, etc. The spatial locations of individual industries were also collected from private sites. Therefore, the sector holds an uncertainty of ± 62%. The other sector comprising various minor sources and their corresponding fuel activities was found to have an uncertainty of ± 28%. The overall uncertainty range of this entire inventory lies within ± 37%, which is in the justifiable range.

4 CONCLUSIONS

A wide number of sources of air pollutants in Bhubaneswar have been identified. For gaseous pollutants, the transport sector remains the dominant contributing sector while wind-blown road dust plays a major role in the case of particulate pollutants. The usage of a maximum number of

personalized and aging vehicles is the main reason for road transport emissions. Diversion of roads to decongestion of traffic flow along with regular cleaning of the dusty shoulders and maintenance of busy roads can be another step to combat air pollution. Besides these, sectors like residential cooking activities and industrial emissions have been emerging as prominent sources of air pollution in the city. Access and availability of cost-effective cleaner solid/LPG gas fuels and their consumption for commercial and residential cooking activities may reduce the pollutant load. Our results focus on the key issues of cleaner air in Bhubaneswar that has to be assessed as per the source-wise strategy and efficient control measures under the NCAP initiative of Govt. of India.

NOMENCLATURE

EI: Emission Inventory
GIS: Geographical Information system
EF: Emission Factor
CO: Carbon Monoxide
NO_X: Nitrogen Oxides
SO_2: Sulfur Dioxide
VOCs: Volatile Organic Compounds
PM: Particulate matter
BC: Black Carbon
OC: Organic Carbon
CPCB: Central Pollution Control Board
BMC: Bhubaneswar Municipal Corporation
HCV: Heavy Commercial Vehicles
LCV: Light Commercial Vehicles
MSLV: Multi-utility vehicles
VKT: Vehicle Kilometres Travelled per day
SAFAR: System of Air Quality and Weather Forecasting and Research
DG: Diesel Generators
BTS: Base Transceiver Stations
OSPCB: Odisha State Pollution Control Board

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SUPPLEMENTARY MATERIAL

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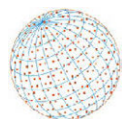
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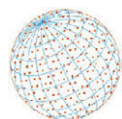
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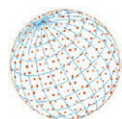
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