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Development and comprehensive analysis of spatially resolved technological high resolution (0.1°×0.1°) Emission Inventory of Particulate Matter for India: A step Towards Air Quality Mitigation

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Abstract: Elevated emission of particulate matter (both $PM_{2.5}$ and PM_{10}) is not limited to urban areas. It's the major pollutant that drives the air quality across the Indian sub-continent as well as across the globe with adverse health impacts. Moreover, India is home to many polluted cities in recent years that are among the list of most polluting cities in the globe. Therefore, the identification of sources of particulate matter and their quantification along with spatial variability has become of paramount importance from the modelling point of view. The present work is an attempt to develop a high-resolution (~10km×~10km) national inventory of particulate (both $PM_{2.5}$ and PM_{10}) pollutants for India for the base year 2020 using IPCC methodology. The study quantifies the emission load from all possible sources in the county using the best possible resolution activity data and bottom-up approach. The estimated annual emission for $PM_{2.5}$ and PM_{10}, are calculated to be 15.8 Tg/yr, and 8.3 Tg/yr respectively. The developed emission dataset is publicly available on Zenodo at https://doi.org/10.5281/zenodo.7885103 (Sahu et al., 2023). Transport-driven windblown road dust remains the dominating source of PM_{10} emission, while transport and industry are the most important sources of $PM_{2.5}$. The unattended anthropogenic source - municipal solid waste burning is found to be emerging as a new threat followed by crop residue burning. The developed new surface dataset has formulated a few recommendations of possible mitigation strategies for India and would be a critical tool for modelling studies.

Keywords: Emission Inventory, Anthropogenic, Particulate Matter, Air Quality, Mitigation

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1. Introduction:

In recent decades, air pollution has been a global concern and is one of the leading causes of mortality, where approx. ~4.2 million people die every year. Nearly ~2.8 million deaths are associated with indoor air pollution globally contemplating it as a modern day curse (Brunekreef et al. 2002; GBDS 2015, 2016). Air pollution is considered as the fifth leading cause for mortality across the globe (HEI, 2019, 2020, 2022). Air quality remains a major environmental health challenge in India. However, the rapid economic growth and inescapable urbanization has stimulated air pollution to such an extent that it continues to pose a threat to public health (Gorai et al., 2018; Beig et al., 2020; McDuffie et al., 2021).During the recent years, urban air pollution has emerged as one of the biggest environmental issues in most of the well-developed and developing countries (Molina and Molina, 2004; Sahu et al, 2011; Venkataraman et al., 2018; Sahu et al, 2023). South Asian countries are currently regarded as one of the major sources of anthropogenic pollutants (IPCC, 2021) where the most emerging economy of South Asia i.e., India has a high urbanization rate of 31% with 416 million urban populations by 2050(UN, 2018). Due to its large population and rapidly expanding economy in Southeast Asia (SEA), it is also major source of air pollutant and greenhouse gases (GHGs) (Streets et al., 2003; Zhang et al., 2009; Permadi et al., 2018). Amidst all hazardous pollutants, both $PM_{2.5}$ and PM_{10} have emerged as pollutant of concern due to their adverse impacts on human health in developing countries. Particulate Matter (PM) is an important pollutant responsible for deteriorating air quality in most of the Asian cities. Particulate matter is root cause of the noxiousness of health (Mukherjee et al. 2017, Manojkumar et al., 2019; Klimont et al., 2017). It can be emitted to the atmosphere as primary pollutants and result from atmospheric aerosol formation where the tiny solid and liquid particles to persist as airborne. The size of the particles is responsible for their potential to cause health problems. Smaller particles less than 2.5µm in diameter are the greatest threat because they can travel deep down into your lungs, and some may even accumulate in bloodstream. Air pollution is responsible for ~1 million premature deaths per year (Conibear et al., 2018; Gao et al., 2018, Chen et al., 2020). The World Health Organization (WHO) reports that 7 million people generally die a premature death due to PM. Similarly, the International Agency for Research on Cancer (IARC) states it is a malignant carcinogen (IARC 2013, Kim et al., 2019). Chronologically, a couple of studies have focused the acute health effects associated with the short-term exposure to airborne particulates (Brunekreef, et al., 2002; Weltman et al., 2021). Many studies across

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the globe have constantly illustrated higher rates of respiratory malfunctioning and cardiovascular diseases because of elevated air pollution where the role of $PM_{2.5}$ is significant.

India is the second largest populated country in the world carrying around 1.4 billion people where the air pollution has emerged as a big challenge (UNDP 2017; Venkataraman et al., 2018: Sahu et al, 2021). Recently 37 cities from India are already in global list of most 100 polluting cities with the high load of PM (WHO, 2014). It is also seen that ~99.9% of the Indian population is currently estimated to live in the areas where the WHO Air Quality Guideline of 10μg/m^{3}was surpassed (Venkataraman et al., 2018; Pant et al., 2018). The impact of regional pollution on climate and the environment has become a focal point in atmospheric science where Indian megacities pose a vital role to play.

The economic upswing of India in recent decades has eventuated a constant increase in trend of air pollutant, which as a consequence, unfolds the up surging relative contribution of emissions of India to that of Asia (Kurokawa and Ohara, 2019). Therefore, understanding the source of anthropogenic emissions in a developing nation like India is an uphill task due to diverse culture and uneven distribution of urbanization and development. As air pollutants are emitted into the atmosphere because of variety of individual sources, it has large spatial and temporal variability. Accurate quantification of these emissions is also challenging due to complex process that includes various contributing sources, the intricacy of their technology and the lack of authentic real time measurements within India (Venkataraman et al., 2018). So, developing a reliable emission inventory (EI) with ultra-precision is of great significance for building air pollution control measures and mitigation strategies. Robust emission estimates are also a critically important factor for studies of regional atmospheric chemistry and climate variability. Emission inventories provide a basic framework in order to understand the sources of pollutants and for reinforcing the measures to control pollution(Mobley et al., 2005; Miller e tal., 2006; Gargava et al., 2014).Earlier, couple of national studies have also made efforts to compile inventories focused on few major pollutants over India (Gargava and Aggarwal, 1999; Garg et al., 2002; Reddy and Venkataraman, 2002a,b; Dalvi et al., 2006; Mohan et al.,2007; Sahu et al., 2008, CPCB, 2010;Beheraet al., 2011; Lu et al., 2011; Gargava et al., 2014; Sahu et al, 2014; Sahu et al, 2015a;Sahu et al, 2017; Beig et al., 2021; Sahu et al, 2021).The above emissions inventories developed, are for older base years with very coarse resolution. In contrast, the emissions are very dynamic in nature, changing with national/regional policy, technology, and lifestyle. Moreover, many inventories are developed using top-down approach where the uncertainty is believed to be very high. These emission datasets do not represent the

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current nation's emission scenario and need to update with bottom-up approach using high-resolution activity data. Apart from this, the resolution of emission inventory is crucial for air quality, climate and regional atmospheric chemistry study (Bond et al. 2004; Ohara et al. 2007; Sahu et al. 2008, 2011, 2014, 2015a, 2017). The finer the resolution the more detailed information of sources is available for regional scale air quality and atmospheric chemistry modelling. Aiming to address these issues, we here present a very high resolution gridded (~10 km ×~10 km) inventoryof tiny ($PM_{2.5}$) and coarse particle (PM_{10}) emission, developed using bottom-up approach, for Indian sub-continent, from both anthropogenic and natural sources and for the base year 2020. We have also formulated possible mitigation strategies based on the present work.

2. Materials & Methodology:

2.1. Sources & Activity Data Used

Particulate pollution significantly varies across the countries in all aspects of its composition, distribution and sources. Hence, the assessment of the wide range of sources of PM emission depends largely on determining the regional sources characteristics. In order to suffice the objective of developing a realistic EI, activity data is of paramount importance. The sources of PM in developing countries are far more comprehensive and diverse than those from developed countries because of the quick metamorphosis between rural and urban economies. According to review of literature, it was observed that the most contributors to PM include basically transport based, industrial sources, cooking, thermal power, fugitive dust and unprocessed biomass fuel like wood, dung and crop residue (Reddy and Venkataraman, 2002 a,b; Garg et al., 2002). Furthermore, large amounts of PM are also injected into the troposphere through municipal solid waste burning, dust from construction activities followed by suspension of dust from both paved and unpaved roads, where meteorological parameters like wind speed and direction hold a substantial role in their genesis. Given the wide distribution of sources of PM, a crucial step towards developing a detailed emission inventory is to identify all attainable major/minor anthropogenic and natural sources which in one way or another is responsible for both indoor and outdoor air pollution.

In this current process, a bottom-up based EFs based approach has been adopted as per IPCC Tier-2/3 approach, which is used extensively. Gathering and later assembling of such high-resolution comprehensive activity data is both an uphill and scrupulous task. Apart from secondary sources, primary data from a couple of on-site active emission campaigns had been carried out for several cities like Delhi(SAFAR-Delhi-2010, 2018),Mumbai (SAFAR-

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Mumbai-2015), Ahmedabad (SAFAR-Ahmedabad-2017), Pune(SAFAR-Pune-2020), Sahu et al., 2021a,b, Mangaraj et al., 2022a, b, which had allegedly been a support in framing similar data set for entire Indian sub-continent.

The gridded $PM_{2.5}$and PM_{10} estimation is undertaken particularly with regard to primary/secondary activity data collected for 16 major/minor sectors: transport, industry, thermal power plants, waste burning, residue burning, construction, waste disposal and treatment, brick kiln, street vendor, cow dung, diesel generator used in agricultural sector, crematory, windblown road dust, cooking activity in slums and residents (household), cigarette smoking, mosquito coils and incense sticks for worship. In term of high resolution spatial information of activities, this inventory includes spatial data of about ~0.62 million village boundaries /and associated population data, ~721 district data, ~1.1 million km of major/minor road network across the country, ~19000 industries, 0.56 million sq km of forest area, agriculture area, ~0.9 million point of interest (PoI), which includes large shopping malls, major hotels, tourist places, railway stations and junctions, hospitals etc. for accurate spatial allocation of emission. The detail of high-resolution proxy information is vital in improving spatial allocation. In the same vein, secondary data is collected from various authentic government sources like MoRTH (Ministry of Road Transport & Highway), DoES (Directorate of Economics and Statistics), NPA (National Power Portal), CEA (Central Electricity Authority), CPCB (Central Pollution Control Board), Ministry of Petroleum and Natural Gas, Census of India, Ministry of Home Affairs, Ministry of Urban Employment and Poverty Alleviation, ICAR (Indian Council of Agricultural Research), Ministry of Agriculture & Farmers' Welfare, MoSPI (Ministry of Statistics and Programme Implementation), Ministry of Housing and Urban Affairs. The details of sectorial (source-specific) activity data, technological emission factor and methodology used for present emission estimation are provided separately hereafter.

a) Transport:

India covers a wide and large road network of approximately 5.89 million km consisting of national highways, state highways, expressways, major and minor roads spread across the all-geographic region. India has been witnessing a consistent increase in the number of vehicles in recent years. Indian vehicle number has grown by more than five folds in the last two decades (Fig.1a). At an approx. 295.8 million vehicles have been registered as of March 2020. Assembling category-specific vehicle numbers across India with reference to the type of fuel used along with several secondary data are obtained from MoRTH. The district-wise on-road

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vehicle activity data were obtained from paid site of Socio-economic statistical data (https://www.indiastat.com/) and Transport Departments of individual states.

The vehicle are broadly classified vehicles into 8 categories: - Two-wheeler (2W), Three-wheeler (3W), Commercial Car (C Car), Personal Car (P Car), Light Commercial Vehicle (LCV), Heavy Commercial Vehicle (HCV), Bus and Miscellaneous (MSLV), further apportioned them based upon their fuel used. The relative contribution of each category to the total number of vehicles plying on-road as of 2020is illustrated in Fig.1(b). The Energy Statistics of India, MoSPI states that the national level fuel consumption for road transport sector tallies~30 MT of petrol, ~89 MT of diesel and ~10.8 MT of CNG consumed annually. According to Petroleum Planning & Analysis Cell, MoPNG India holds ~2207 CNG stations as of March 2020 with highest no. of CNG stations in Gujarat (636), Delhi (419) and Maharashtra (370).

On-road vehicle emission depends on various factors like vehicle type, vehicle emission control, age of the vehicle, and Vehicle Kilometers Travelled (VKT). Category-specific VKT per day per vehicle is an important parameter that determines the magnitude of traffic in a particular region associated with the pollution load. Therefore, VKTs was observed keenly from our recent studies SAFAR-Delhi-2010, 2018; SAFAR-Mumbai-2015, SAFAR-Ahmedabad-2017, SAFAR-Pune-2020 and were analyzed before consummating VKTs for national scale. Classifying the number of vehicles according to their age is sensitive and modulate the emission siginificantly. A load of aging vehicles accounts for ~28.5% which belongs to >15 years old category as shown in Fig.1(c). As reported by the Ministry of Road Transport and Highways, vehicles older than 15 years will be prohibited with effect from 1st April 2022 as they cause 10-12 times more pollution than present-day vehicles. However, in the absence of an effective vehicle scrapping policy, these vehicles are still active in the country.

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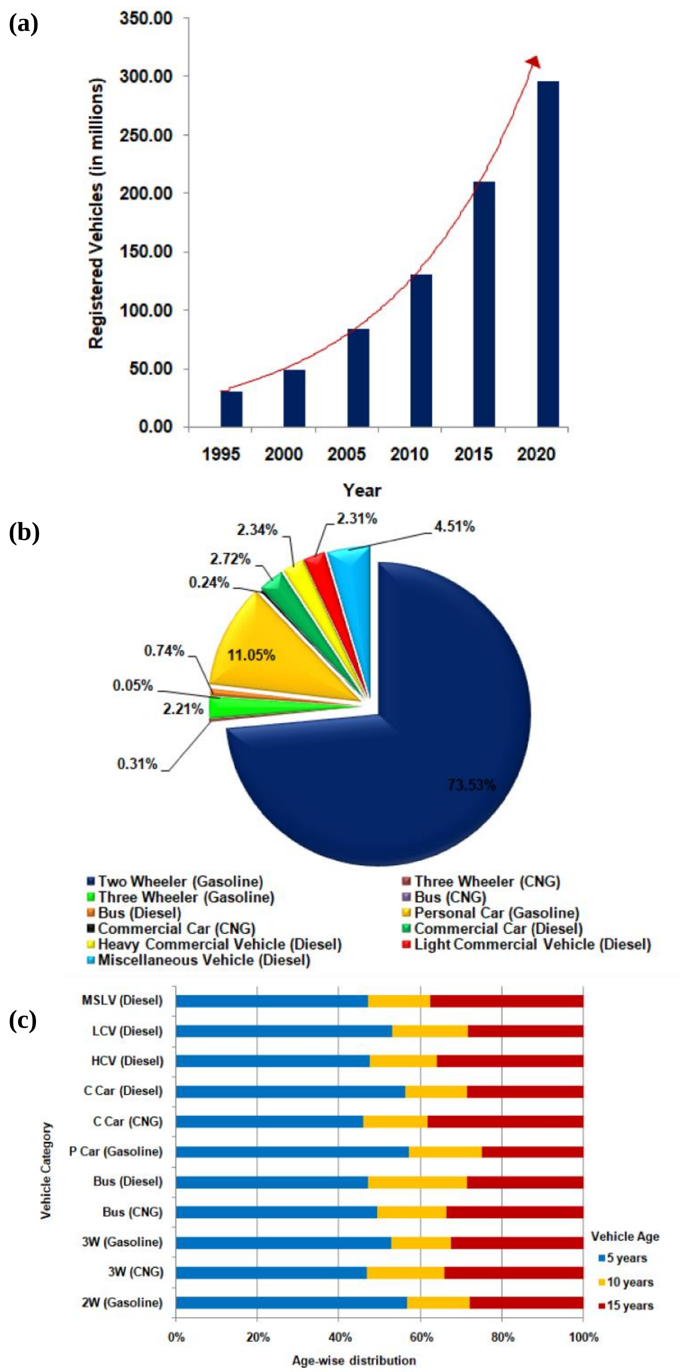

Fig.1. Growth of vehicles in India (1995-2020); Relative contribution of each vehicle category to the total number of vehicles; Age-wise distribution of vehicle category

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b) Wind-blown road dust:

Road dust has always remained a critical and dominating sector in emission inventories for the Indian geographical region. Road dust resuspension due to the movement of the vehicle is a very common phenomena and contributes predominantly to the PM_{10} and $PM_{2.5}$ load in the atmosphere. High silt loading along with rough and miserable road conditions with congested shoulders are the prime reason for the resuspension of dust. Along with this, modulating factors like on-road vehicle percentage, surface moisture content, surface silt load, average precipitation days, mean vehicle speed, and average vehicle weight of the vehicle are significantly essential for estimation. According to the MoRTH, the road network (Fig. 2e) of India is densely distributed around 6.7 million kilometers (2020) as stated earlier and ~71% of road runs through rural India, and the rest 29% runs through urban areas. Therefore, every parameter involved was analyzed both in terms of rural and urban road conditions of India.

Amato et. al., (2017) reported that the silt load varies significantly from major busy roads to the minor slower ones. It indicated that traffic intensity, fleet composition, and paved/unpaved road conditions are directly proportional to road dust resuspension. The surface silt content for rural areas was considered to be 36% because of the larger fraction of unpaved roads. Similarly, the urban region holds a silt content of 30% due to a higher paved road ratio. The resuspension of dust due to vehicle-induced activities is a complicated phenomenon that is also affected by vehicular weight and speed (Gillies et. al, 2005). The HCV share is substantially responsible for pulverization of coarser particles into finer dust, resulting in elevated rate of resuspension emission. The weight of the vehicles differs widely depending upon its model, engine, and load factor. In the present study the average weight of the vehicles used in rural scenario for 2W, 3W, 4W, Bus, HCV, LCV, MSLV are 0.2, 0.03, 0.10, 0.05, 0.26, 0.17, 0.51 tons respectively. Similarly considering the urban scenario the average weight was estimated to be 0.17, 0.02, 0.25, 0.12, 0.68, 0.15, 0.59 tons for the same vehicle categories respectively. The comparison between average weight of vehicles for rural and urban regions reflects an increase in the case of urban areas representing the possibilities of heavier road dust resuspension. On the other hand, the number of precipitation days decides the surface moisture content. The higher the moisture the lesser is the dust resuspension and vice-versa. District-level annual precipitation days were adopted from the Indian Metrological Department's (IMD) Rainfall Statistics of India, 2019, which ranged between 4-6% for urban and rural regions.

c) Industry:

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Air pollutant emission from industries specifically eventuates due to combustion related activities that involve burning of fossil fuel. Our study accounts for~19000 industries of different types over Indian subcontinent, specifically dominates over megalopolis regions. They are mostly concentrated in the industrial zones of states like Maharashtra, Gujarat, Tamil Nadu, Delhi, Karnataka, Andhra Pradesh and Odisha. Major industries include iron and steel industries (~764), cement (~235), engineering (~1684), textile (~1674), agro-processing (~930), chemical (~910), and many micro-, small- and medium-scale industries. The production capacity, fuel consumed, and technology used regarding industries was adopted from government sources like Ministry of Petroleum and Natural Gas, MoSPI (Ministry of Statistics and Programme Implementation) and Ministry of Micro, Small, and Medium Enterprises (MSME) India. According to the Energy Statistics of India, the major dominating fuel consumed by the industrial sector for coal, lignite, diesel, low sulphur heavy stock (LSHS) and furnace oil (FO) accounts to be ~296 million tonne (MT), ~6MT, ~0.3 MT, ~0.04 MT, and ~2.4MT respectively. The processing and energy/fuel consumed along with fuel specific technological emission factors are involved in estimating the total industrial emission. The spatial distribution of industries is illustrated in Fig.2 (f). Industrial emissions were spatially distributed based on their locations over the country.

d) Thermal Power Plant:

Energy demand in India has been growing rapidly as remarkable progress has been made in providing electricity to maximum parts of the country. Coal-based thermal power plant is the largest source of electricity in India. According to the Ministry of Power, ~52% of India's electric power generation is fulfilled by the coal-based plants, 26.1% by wind, solar & other renewable energy-based power plants, 12% by hydroelectric-based power plants, whereas, the lignite, gas, nuclear, and diesel-based power production techniques contribute to the remaining 9.9% of consumption. The Ministry of Power reported that the total installed capacity of coal-based power plants over India is ~208624.2 MW as of 2020. The plan-wise growth of installed capacity in the country stated that there has been a linear increase in total installed capacity of India with 199877MW in 2012 and 370106 MW. The average electricity use is ~1208 kWh per capita for the financial year 2020. This is also expected to expand much more rapidly in the upcoming decades. The Growth of Electricity Sector in India, 2020 reported that ~5 lakh villages of India were electrified. The annual reports of the National Power Portal and Ministry of Power, have detailed information regarding the total number of operational units, technology used and fuel usage. The spatial location of individual thermal power plants is illustrated in Fig. 2(g).

The role of coal-fired thermal power plants is huge in terms of providing electricity and coal combustion. Thermal power plants of India adopt several technologies with unalike operating conditions. The power units are categorized broadly into three i.e., subcritical, supercritical and ultra-supercritical. The supercritical plants consume less fuel and have increased efficiency than the subcritical. Ultra-supercritical plants are the most advanced ones with enhanced coal technology as they require less coal per MWh, bringing down emissions. Generally, power plants maintain a coal stock record, which holds the actual coal consumption in power plants and coal supplied during a particular period. The CEA states that the daily coal requirement is based on the maximum coal required for actual consumption of the plant or the coal required for an installed capacity of the plant at 55% plant load factor (PLF). India has consumed ~611.4 MT of coal and ~36.3 MT of lignite by the thermal power plants to meet the electric demand. The thermal power station with the highest installed capacity in Northern India is Rihand Thermal Power Station with an installed capacity of 3000 MW. Similarly, to the West is Vindhyachal Super Thermal Power Station with an installed capacity of 4760 MW, Barh and Talcher Super Thermal Power Station in East India with 3300 MW of installed capacity, and Ramagundam Super Thermal Power Station in the South with 2600 MW of installed capacity.

e) *Household and Slum:*

In a country like India, with diverse cultures and a multi-level society, the census always stretches a snapshot of the demographic profile. India holds a population of ~1.38 billion dispersed over 36 states and union territories, of which a large fraction (~65%) resides in is the rural India. The remaining 35% dwells in the urban suburbs. Residential cooking has remained one most responsible reason for morbidity and mortality rates due to indoor air pollution in India (Global Burden of Disease Study, 2019). The residential sector involves cooking activities, which include heating of water, use of traditional stoves (chulhas), and use of solid fuels. The type of technology used for cooking in city and village populations varies by large. India is also urbanizing rapidly as more people migrate from rural areas to the cities, which is one of the reasons for mushrooming of slum clusters across five major megacities like Delhi, Mumbai, Kolkata, Bangalore, and Chennai. The National Buildings Organization (NBO) under The Ministry of Housing and Urban Affairs, Government of India in 2015, reported that ~17.4% of slum population belongs to the total urban population of State/UTs-India and

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~22.4% of slum population belongs to the total population of metro cities/towns. The Handbook of Urban Statistics of India, 2019 reported that, according to the UN World Urbanization Prospects, 2018, ~55.29% of the world's population resided in urban areas in 2018 when 34.03% of the urban population in India dwelled in slums. It also estimated an average annual growth rate of the urban population of the world ~1.90% during 2015-20. Considering this and the advancement of urbanization in India at present, it is estimated that ~35% of India's urban population lives in slums. In slums, the level of air pollutants is seemingly higher than in non-slum settlements due to their practice of unclean cooking fuel and most of the impoverished slum localities stand in the vicinity of industrial zones as well as city center.

The living standard of people in a slum is substandard without access to many government's benefits like LPG connections, below poverty line (BPL) ration cards, etc. Moreover, the poor waste disposal management, open burning of wastes and trash, the type of fuel, and the quantity used restraints to assess the air quality in slums. The fuel consumption pattern throughout the country portrays a picture where it is estimated that ~46.32 MT of wood is used as the primary fuel for cooking activities. Enforcement of LPG schemes has become prevalent since 2011, but only ~22.4 MT of LPG as major residential fuel. Additionally, the use of cow-dung/upla for residential cooking in India is also of larger proportion. Unlike these, the practice of using raw fuel like coal and kerosene is ~8.12 MT. The per capita fuel economy with respect to type and quantity of fuel used for residential cooking is estimated after referring and analyzing the fuel statistics of Household Amenity Census 2011, Venkataraman, 2018, Energy Statistics 2020, and Council on Energy, Environment and Water, 2020. Despite the implementation of the Pradhan Mantri Ujjwala Yojana scheme, 2012 (MoPNG, 2018) the use of cleaner fuels (LPG) is comparatively less to the use of raw fuel like coal, wood, kerosene, and cow-dung (upla). India's rural population, which is a massive proportion and the lower income households, still uses fuelwood as primary as well as secondary cooking fuel along with other solid fuels which lead to increase in pollution levels.

f) Street Vendor:

Street vending is a profession that has been in general practice in India in a much-unorganized manner since time immemorial. Urbanization has also given rise to a booming number of street vendors. Street trade has become one of the visible self-employment occupations across India and is also likely to rise substantially. Similarly, street food has also become much popular as it is readily available and is comparatively cheaper than big hotels and inns. Mobile food carts

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have become a trend across cities throughout the world (Nahar, 2020). Lessons can be drawn from megacities like Mumbai and Delhi, which hold at least 3-5 lakh street vendors, where only a few of them are registered under Municipal Corporations and maximum vending zones are unauthorized and unsystematic. According to the National Sample Survey Office (NSSO), ~1.18 million households depend on street vending as their major source of income. Considering the population growth and rise in the present urban population, according to the Government of India's Street Vending (Protection of Livelihood and Regulation of Street Vending) Act there are ~10 million street vendors in India (Narang, 2020).

The SAFAR field campaign of the Ministry of Earth Sciences carried out across the major cities Delhi, Mumbai, and Pune reported that the commercial cooking activities predominantly involved the use of raw fuel (coal, fuelwood) and LPG as the primary source of fuel (SAFAR-Delhi-2010, 2018; SAFAR-Mumbai-2015, SAFAR-Pune-2020). This had led to the rise of an unattended source that has quite a large involvement in air pollution. Due to population growth, it is expected to reach heights in upcoming decades as people have become more dependable on readily available food at a lower price. The practice of charcoal grilling could be regarded as a significant source of PM, CO, and ultrafine particles. Consumption of coal is estimated to be around ~20-30 kg/day. Fuel wood is another prime fuel being used widely due to its easy availability. They use commercial-grade LPG cylinders of 17.9 kg capacity per month. Due to lack of proper statistical information regarding the commercial cooking fuel type and its consumption pattern by the street vendors the SAFAR emission inventory campaign reports were referred to and decoded for national scale.

g) Crop Residue Burning:

The enormous amount of crop residue is generated every year, which are generally used as animal feed, thatching for roofs in rural houses, fuel for domestic cooking etc. Despite that, a large portion of the crop residue is still left unutilized in the fields, which are opted by farmers for burning as it is one of the convenient methods to remove waste and later is believed to be productive and nutritive for the crops. Here, eight different types of crops viz. wheat, rice, sugarcane, maize, mustard, groundnut, coarse cereal and cotton are taken into consideration. These crops grow profoundly throughout the country in different states. The coarse cereal here includes pearl millet (bajra), sorghum (jowar) and barley.

The activity data for the crops like cultivated area, their production and yield are obtained from government sources like ICAR (Indian Council of Agricultural Research), Ministry of Agriculture & Farmers' Welfare, MoSPI (Ministry of Statistics and Programme

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Implementation). The annual production of crop types considered for this study was estimated to be ~700MT for the base year 2020, which includes major crops such as rice, wheat, maize, mustard, groundnut, sugarcane, coarse cereals, and cotton. Period of sowing, harvesting and post-harvesting across Indian states were compiled from ICAR and Ministry of Agriculture &Farmers' Welfare. India produces nearly ~624.3 MT of crop residue annually with wide regional variability. Approx. ~150.7MT of residue is being burned on field. The amount of residue generated for a particular crop type is reported in Mangaraj et al, (2021). To improve the spatial allocation and the trend of fire counts, the satellite-ground data of monthly active fire counts of MODIS-C6 from the NASA-FIRMS were referred. The detailed information about the activity data and modulating factors used for crop residue emission estimation as well as its seasonal variation at very high resolution can be referred in our recent study Sahu et al., 2021b.

h) Cow-dung (Biofuel):

In India, animal manure is used in biogas plants. The cattle population in India is also quite dominant worldwide which is why access to dung becomes frequent. Cows are generally kept by households for their domestic purpose from which use of cow dung as fuel is one objective. It also contains a significant amount of energy, which is why it is used as solid biofuel for cooking purposes in domestic hearths or traditional open stoves (chulhas) without a proper ventilation system, especially in rural India. Cow-dung cakes are made from the by-products of animal husbandry (specifically cow), which are traditionally used as fuel in India. The collected cow dung is moulded into circular shapes leaving a curvature to let it stick to the walls for sun-drying. Later, they are stacked into piles and reserved for use as a replacement for firewood. In common language is referred to as ‘Upla’.

Around 896 million people reside in Indian villages where access to LPG connection is still challenging and limited. According to a United Nations Industrial Development Organization (UNIDO), over two-thirds of India’s 1.3 billion people still rely on cow dung not only as their primary but also as secondary fuel options for cooking activities due to its easy availability and especially during winters for boiling water. Cow dung is associated with a high level of indoor air pollution. The burning capacity of cow dung is dependent on its moisture content and the amount of heat released during combustion. At least 30kg of cow dung is consumed per month by a single household for their day-to-day cooking activities (SAFAR-Delhi, 2018).

i) *Diesel Generator:*

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India's power sector has always struggled to provide extensive, uninterrupted, and reliable grid supply, where diesel generator sets serve as a great alternative, as well as power back-up, in prominent sectors like agriculture, construction, industry, plants, households, telecom, hospitals, and other commercial applications. Uninterrupted power supply force people to rely on diesel generators (DG). The diesel generator sets market in India has both organized and unorganized manufacturers. The diesel gen-sets are used as a backup in commercial complexes and residential societies. Nevertheless, the large fraction of total generator demands comes from the agriculture sector due to poor grid power penetration. According to the International Energy Agency (IEA), the estimated use of diesel gen-sets in agricultural irrigation accounts for ~8.8 million units. The Department of Telecommunication (DoT), 2019 reported unprecedented growth in the telecommunication sector that has triggered an exponential increase in cellular towers. The fuel consumption pattern is as per reported in Sahu et al., (2015b). Diesel gen-sets ranging between the size of 2 kVA to 7000 kVA are used mostly in the country with 75kVA especially being more widespread. Keeping the usage of diesel gen-sets in various sectors, the demand for total fuel is estimated to be around ~11MT per year.

j) Municipal Solid Waste Burning:

Waste is a growing environmental and social issue for all modern economies. The characteristic of waste depends on lifestyle and topographical background, which vary from one country to another. Wastes nowadays are exceeding the economic growth imposing its impacts on every individual as well as the environment (Sahu et al, 2021). In the Indian scenario, major cities like Delhi, Mumbai, Kolkata, Bengaluru have huge dumping sites like Okhla, Deonar, Dhapa, and Mavallipura with a daily inflow of more than a thousand tons of waste. Many studies confirm the high concentration of these pollutants at burning sites. As per CPCB, the solid waste generation rate lies between 0.2 and 0.3 Kg/capita/day in small towns/cities with populations less than 0.2 million. State-specific MSW generated were also referred from Annual Report of Implementation of Solid Waste Management Rules, 2019. For cities with a population ranging 0.2–0.5 million, 0.5–1 million, and above 1 million it is usually 0.3-0.35 Kg/capita/day, 0.35-0.4 Kg/capita/day, and 0.4-0.6 Kg/capita/day respectively. We have considered 115 cities based on population ranging from 0.5 million and above. The waste generated per capita varies significantly from city to city as well as in rural areas. In India, the officially reported annual municipal solid waste generated is 53 MT per year, but considering the population dependent per capita MSW generation factor, the actual waste produced is much higher. The total waste generated from these cities along with the other regions of India was

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estimated to be ~194MT. Currently, in India according to the MSW Rules, major fraction i.e., 43% of total municipal solid waste (MSW) is used for land-filled, another ~23% is treated and the rest 34% is openly burned to prevent the dumping ground from overflowing with waste. Most of the cities and towns in India do have a waste collection facility and landfill sites, to inhibit the burning of the solid waste directly inside cities. On the other hand, there is no such organized and efficient waste collection facility for the rural areas of India and therefore openly burned arbitrarily. This scenario was quite visible from the estimations where ~74% of municipal solid waste generated belonged to regions apart from cities with ~24% of total MSW generated.

k) Municipal Solid Waste Treatment Plant:

Waste-to-energy plants burn MSW, in order to produce steam that in turn generates electricity through steam turbines. Incineration of wastes is an efficient way to get rid of waste problem as well as to reduce the emission as compared to incomplete combustion at landfill site. At the same time, incineration process reduces the demand for landfill space as well. The combustion process results in the release of carbon dioxide and other greenhouse gases. As per the Central Pollution Control Board, India has 10operational waste-to-energy plants in the states of Andhra Pradesh (Vishakapatnam, Guntur), Chandigarh, Delhi (Ghazipur, Narela, Okhla), Goa (Saligao), Madhya Pradesh (Jabalpur), Telangana (Jawaharnagar), Uttar Pradesh (Barabanki). The total installed capacity of the operational plants accounts ~94 MW treating a total of ~7965 tonnes of municipal solid waste per day. Delhi is the leading state having three waste-to-energy plants with a total installed capacity of 52MW, which incinerates around 5750 TPD of solid waste. Andhra Pradesh the second highest state to have two waste-to-energy plants with a total installed capacity of 30 MW treating ~1315 tonnes of solid waste per day. Installation of another 16 waste-to-energy plants have already been proposed but are yet to be operational.

l) Construction activity:

Construction activity is associated with the development and modernization of cities in India. Construction sites are source of dust, which can travel far in air. Construction activities include various operations like land clearing, operation of vehicular activities in demolition, debris removal, site preparation, loading and unloading of raw materials, bulldozing, and working with toxic materials. The guidelines on dust mitigation measures in handling construction material, Construction & Demolition (C&D), do have abatement measures for waste generated on- and off-site. The C&D waste management rules passed in 2016 stated that building material, debris, and rubble resulting from any construction, remodelling, repair, or demolition

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of any civil structure of a private or government property shall be regarded as C&D waste and need to therefore abide by the rules. Yet cities have failed to execute proper management. According to CPCB, 70% of the buildings that will stand by 2030 are yet to be completed. It is difficult to determine the construction sites across the country due to a lack of reliable data availability. Megacities Delhi and Mumbai have lately remained in headlines for their dust load due to construction activities. As major cities are much involved in the building of well-constructed roads, flyovers, roads, freeways, expressways, skyscrapers, building blocks, multi-complexes, and new establishments, therefore, weightage was given to the major cities. In this study, we have included activities demolition and debris removal – bulldozing, vehicle movement on construction site (unpaved roads), and site preparation – bulldozing, scrapers unloading and removing topsoil. The major source of particulate matter at construction sites involves the movement of vehicles and heavy equipment, which readily combine with other toxins in the atmosphere and increase the risk of inhalation of those particles. The use of heavy commercial vehicles and multi-utility can lead to suspension of dust.

m) Brick Kiln:

The brick making industry is an unorganized small-scale industry that is scattered across India (Lalchandani and Maithel 2013; Pandey et al. 2014; Rajarathnam et al. 2014). Apparently, the traditional brick making industry is the backbone of urban development in India, which is also second largest producer of bricks in the world. The brick kiln industries are flourishing due to the increase in demand of bricks due to rapid economic growth and urbanization. But in due course of time, this sector it has turned out to be one of the largest consumers of coal in the country. Several technologies are being adopted by the brick kilns where the most widely use technology is Fixed Chimney Bull's Trench Kiln (FCBTK). Other firing technologies that are not much popular are semi-Zigzag, Hoffman, Vertical Shaft Brick Kiln (VSBK) and Down Draught Kiln (DDK). Apparently, traditional kilns such as DDKs, and FCBTKs produce huge amount of emission in contrast to VSBKs and Zig-zag kilns (Weyant, et al., 2014; Seay et al., 2021). The practice of older inefficient technologies that has slow combustion (smoldering) and limited control for emission is responsible for huge emissions from brick manufacturing sector. According to the CPCB, only 20% of FCBTKs have shifted to Zigzag kilns and the progress is slow. India produces ~280 billion brick annually (Rajarathnam et al. 2014), where 65% of total brick production is from the Indo-Gangetic plains. Punjab, Haryana, Outskirts of Delhi, Uttar Pradesh, Bihar and West Bengal are also brick producing regions. The brick kiln sector consumes ~35 MT of coal annually (Seay et al, 2021 and Rajarathnam 2014). Many

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kilns in rural and semi urban areas generally use cheap, low-quality fuels such as biomass (rice husk, mustard husk/tudi and bagasse), wood/sawdust, old tyres, ashes, discarded engine oil/kerosene, and plastic. Coal is widely used as fuel but in many cases fuel is mixture of coal around 60% along with solid fuel like crop residue (25%) and rubber (15%). Studies by CPCB suggested that switching to cleaner kiln types would contribute not only towards reducing the CO and PM emissions by 60-70%.

n) Incense stick/ Mosquito coil/ Cigarette:

The burning of incense sticks is another source of indoor air pollution and is very country-specific due to culture and lifestyle. Unlike cigarette smoking, it is widely being used in Indian households as well as business communities. India celebrates different festivals throughout the year where the incense sticks is being widely used. There are various types of incense, including sticks, joss sticks, cones, coils, powders, rope, rocks/charcoal, and smudge bundles. Weight of incense stick, composition, daily per capita usage by households and street vendors. The average weight of incense sticks burnt varies from 20-100g depending on the type used. They are composed of biomass ~45%, coal ~15%, resin (jigit) ~15%, bakhoor (wood chips) ~25% per incense stick. Mosquito coils are also widely being used and source of indoor air pollution. The average weight of mosquito coils is ~12-16g. The incomplete combustion of coils (includes biomass (40%), wood dust (40%), and charcoal (20%)) leads to high emission. There are approximately 120 million smokers in India and according to the WHO, more than 10 million die each year due to tobacco consumption in India. Around 12.95% of the adult male population smoke cigarettes. The activity data considered in the present study is collected from Cohen et al., (2013) and Kumar et al., (2014).

o) Crematory:

According to a government census reports, every year more than ~5 million people die every year in India. The crude death rate for India has been reported to have a decline from 8.6 per 1000 people in 2000 to 7.3 per 1000 people in 2020. The cremation of a body is a religious action performed for the final disposition of a corpse. Most of these are cremated as per traditional ritual style in open area ground. This traditional Hindu funeral pyre system is an ancient ritual that has been practised since ages in which cremated bodies are burned by using firewood in an open ground. These result in deforestation and air pollution. A traditional pyre takes six hours and burns ~450-550 kg of wood (SAFAR-Delhi, 2018), which accounts ~3.82MT of wood used for crematory per year. Apart from electric crematory (10%), the traditional method of cremating by using wood (90%) as fuel is still in practice in India. In this work, district-wise emission from crematorium at both rural-urban levels is calculated based on the district-wise religious population following traditional funeral pyre system. The data of death rate by the Ministry of Home Affairs, Govt. of India, for each state was used for district belonging to the respective state in alliance with the religion type.

The spatial location of major activity data is illustrated in Fig.2 (a-h)

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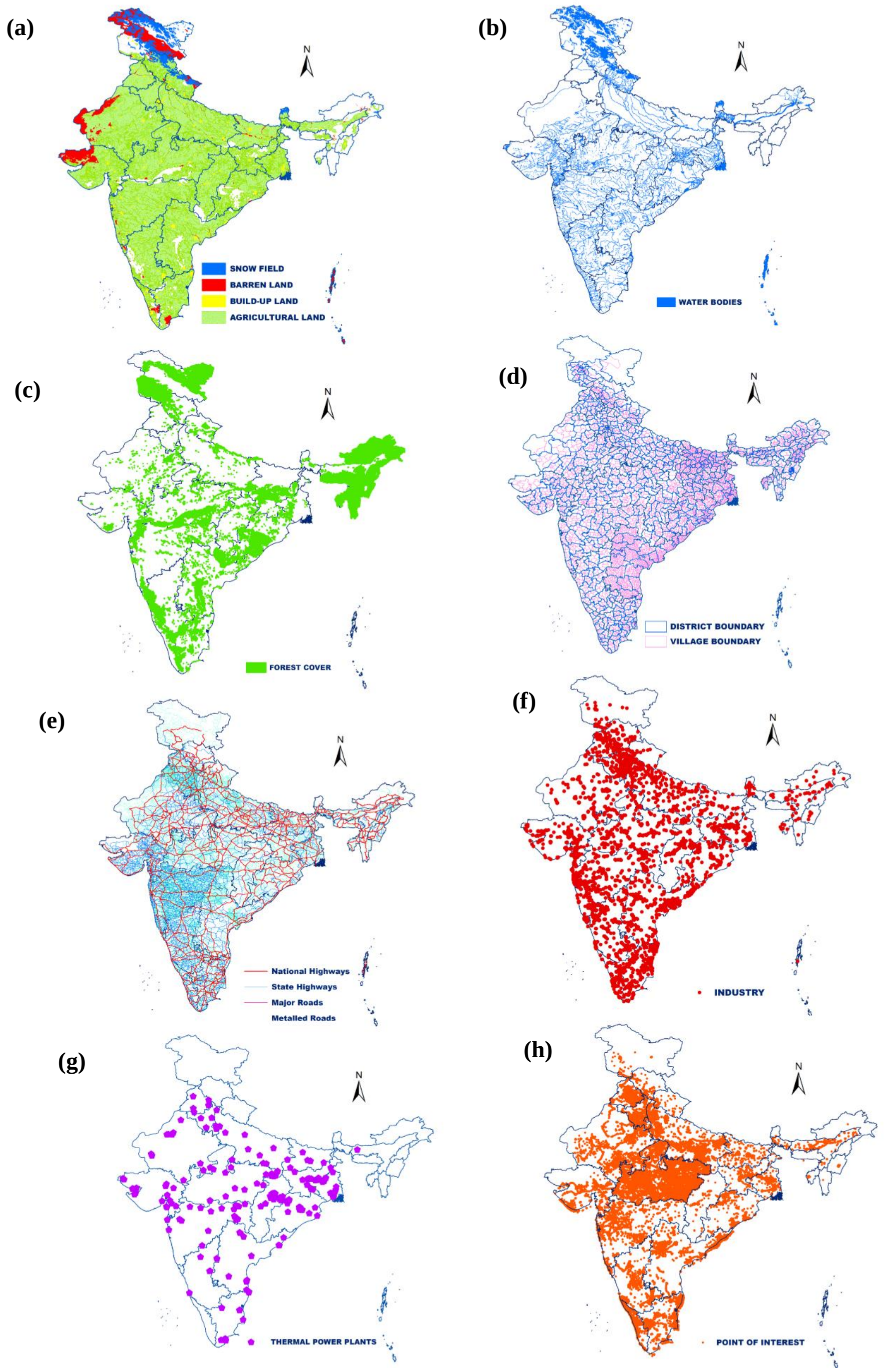

Fig.2: (a) Land cover (b) Water bodies (c) Forest cover (d) District and Village boundaries (e) Road Transport Network (f) Industries (g) Thermal power plants (h) Point of interest

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2.2. Emission Factors & Methodology:

The emission factor (EF) is very sensitive parameter and has a vital role in modulating the quality of inventory data preparation and associated uncertainty. EFs are highly dependent on type of combustion technology used, type of fuel, chemical composition of fuel used and its usage, and emission control. The emission factors used for different fuel types for the industrial, thermal power plant, residential, and other commercial sectors are adapted from several recently published work (Sahu et al., 2023, 2021a, 2021b, 2020; Mangaraj et al., 2022a, 2022b). The appropriate scientific justification and judgement are discussed and elaborated. Further, the methodology to estimate the emissions is similar to that adopted by us in Sahu et al., 2023a.

2.3. GIS based spatial allocation of emission:

Spatial disposition of the emissions is a complex process for modelling and analysis. Geographic Information System (GIS) has the ability to overlay spatial location with the gridded cell layout in order to facilitate the accurate source data by aggregating the control points in each cell. The GIS-based statistical methodology is widely used in emission inventory. Indian geographical region consists of 721 districts and geographically it is covered by 30185 grid cells, each having 0.1° x 0.1° resolutions. As the value of emission in gridded cells consists of several sectors that contribute to total emissions, they are organized systematically in the form of thematic layers so that it could be analysed individually. The transport sector over the Indian sub-continent involves a wide and large road network of approximately 5.89 million km, which was used as proxy. The district-level boundary layer accompanying the number of vehicles registered i.e., ~29crores and its corresponding emission throughout the 721 districts of India was overlaid across the gridded layer. The emission later superimposed on the road network was distributed based upon the national highways, state highways, major, and minor roads networking the industrial zones. Similarly, a load of wind-blown road dust over the paved and unpaved roads of India was accomplished. Industrial sector is one of the vital and spatial locations of around large size 19000 industries in India was adopted and extracted on each grid cell. The weightage according to the most polluting industries was distributed to calculate the gridded emission. The spatial location of ~ 201 thermal power plants with their installed capacity fostered as a foundation for assigning emission load over those specific grids. Districts (~721), sub-districts (~6080), village boundaries with nearly 0.62 million villages in India, and population data, etc. are a critical input for calculation of emission from sectors like residential, slum, street vendor, crematory, municipal solid waste burning, incineration plants, incense sticks/mosquito coils/cigarettes,

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diesel generator and cow-dung (biofuel). As these sectors are dependent on the above GIS factsheet as their primary baseline so along with the per capita utilization and fuel activity data, emission was distributed spatially over the grid cells which demonstrated emission load reference to the actual scenario. Aviation sector with their landing and take-off activity data was prepared by their real-time destination and source accountancies. In conjunction with the exact geo-referenced locations of airports over India, accordingly emission was assigned to those specific grids. Allocating spatial position of brick kilns all over India is in itself a herculean task as no robust pre-constituted data is readily available. Hence identifying the exact locations of brick kilns was done with the help of Google earth pro and later geo-referenced based on our GIS attribute data. In the case of crop residue burning, there is very little detail on the methods to extract burned areas for the emissions calculations. Accurate burned area estimates are notably difficult to extract in the cropland area. Hence information such as ground fuel loading, combustion efficiency, emission factors, and the satellite-ground data integration method by considering the NASA FIRMS monthly active fire counts of MODIS-C6 for the required base year (https://firms.modaps.eosdis.nasa.gov/active_fire/#firms-shapefile) was adopted to calculate the seasonal gridded emission load on Indian sub-continent.

3. Result and Discussion:

In the present study, the total $PM_{2.5}$ and PM_{10} are estimated to be ~8332.35 Gg/yr and ~15797.76 Gg/yr respectively. The sector-wise emissions are shown in Table 1. An open-access dataset has been provided at https://doi.org/10.5281/zenodo.7885103 (Sahu et al., 2023) for $PM_{2.5}$ and PM_{10} emission from a broad spectrum of 17 major and unattended anthropogenic sources at high-resolution (0.1°×0.1°) for the Indian subcontinent.

Table 1: Sector-wise $PM_{2.5}$ and PM_{10} Emission in India for base year 2020

Sl. no.	Major Sectors	Sub-Sectors	$PM_{2.5}$ (Gg/yr)	PM_{10} (Gg/yr)
1	**Windblown-Road Dust**	-	**471.90**	**4371.60**
2	**Transport**	-	**1586.30**	**1635.41**
3	**Industry**	-	**1190.89**	**1626.73**
4	**Thermal Power Plant**	-	**388.62**	**1489.71**
5	**Residential**	Household	251.22	359.08
		Slum	529.15	675.46
		Street Vendor	521.45	919.15
		Crop Residue Burning	1023.48	1286.58
		Cow-Dung (Biofuel)	80.83	101.04
		Diesel Generators	272.90	341.12

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	Total Residential		**2679.01**	**3682.41**
6	**Other**	Municipal Solid Waste Burning	782.29	842.46
		Municipal Solid Waste Treatment Plants	61.83	63.09
		Construction	352.04	880.11
		Brick Kiln	612.33	949.78
		Incense Sticks/Mosquito Coils/Cigarettes	160.35	197.99
		Crematory	46.78	58.47
	Total Other		**2015.61**	**2991.90**
Grand Total Emission			**8332.35**	**15797.76**

3.1 Spatial distribution of emissions:

The distribution of the total national PM_{10} emission of 15.8 Tg/yr is illustrated in Fig.3. The spatial pattern of PM_{10} emission shows clear regional distribution, with high values in the order of 11.5–86 Tg/yr/grid of $PM_{10}$is found over the upper Indo-Gangetic Plain (IGP) area as well as some parts of Western and Southern parts of India. The elevated emission in the above regions is due to high rural population density and associated traditional activities. It is also found that road network is quite dense in IGP region, Southern and Western India. In addition to this, establishment of industries in these areas push mass of people to migrate from surrounding regions, which are one of the elements in propelling such high emission. Considering all the 16 major/minor sectors, the spatial distribution is done by segregating them into six major sectors viz. transport, windblown road dust, industry, thermal power plants, residential and other sector as shown in Fig.4 (a-f). The spatial distribution of $PM_{2.5}$ (8.3 Tg/yr) is substantially similar that of total PM_{10} emission pattern. PM_{10} being the most prevalent pollutant with regard to its adverse impacts on health and environment, emphasis has been given to spatial distribution of PM_{10} emission here. The PM_{10} emission for transport, windblown road dust, industry, thermal power plants, residential and other sector are estimated to be 1635.41 Gg/yr, 4371.60 Gg/yr, 1626.73 Gg/yr, 1489.71 Gg/yr, 3682.41 Gg/yr and 2991.90 Gg/yr respectively. These 6 major sectors hold the emissions of other minor sectors under them as mentioned in the table earlier. Both Fig.3 and Fig.4 depicted clearly that the emission is quite high in upper IGP.

With respect to gridded spatial PM_{10} emission, the elevated emission grid falls over the Delhi and surrounding regions which have dominating sectors windblown road dust with ~70.6 Gg/grid/yr, transport with ~9.2 Gg/grid/yr, residential ~3.3 Gg/grid/yr followed by industrial and power plants. This could probably be due to the amalgamation of the high vehicular density in densely populated area, high usage of solid fuel like biofuel, coal, kerosene use in slum

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pockets, commercial cooking and street vendors in Delhi-NCR. The geographical location of Delhi makes it an inland as it is surrounded by is bordered by Uttar Pradesh in east and Haryana to the west, south and north, which is why this region stands as the most polluted hotspot. In term of gridded analysis, just 10% of Indian geographic region (districts) contributes nearly 4.69 Tg of emission annually and the district-wise analysis of the emission from all the sectors shows a significant change in number with respect to the sectorial variation. The windblown road dust emission of 1.2 Tg/yr being the most dominating sector followed by the residential 0.9 Tg/yr and the industrial sector with 0.8 Tg/yr. The power and other sectors each with 0.6 Tg/yr leaves the transport sector (0.4 Tg/yr) to the bottom. Top 100 polluting districts contributes nearly 40% of national total emission where these districts are more confined over state like Delhi, Punjab, Haryana, Uttar Pradesh, West Bengal, Bihar, Chhattisgarh in the IGP region; Gujarat, Rajasthan, Maharashtra towards the Western region Madhya Pradesh in the central, Odisha, Jharkhand to the East and Andhra Pradesh, Kerala, Tamil Nadu, Telangana, Karnataka in the South India. In the case of transport and windblown sectors, the most dominating districts are Bangalore, Chennai, Ahmadabad, Kolkata, Thane, Surat, Pune and Mumbai Suburban. The pattern shows that the megacities are the maximum contributors due to the dense vehicular load over those regions. Similarly in case of power sector Singrauli, Sonbhadra, Kachchh, Raigarh, Anugul, Korbastands out to be highly emitting and for industrial sector Delhi, Bangalore, Pune, Ghaziabad, Belgaum, Rangareddy, Ahmadabad and Hyderabad were recorded as most dominating districts. Along with this higher growth in population and urbanization are key reasons for the elevated emissions.

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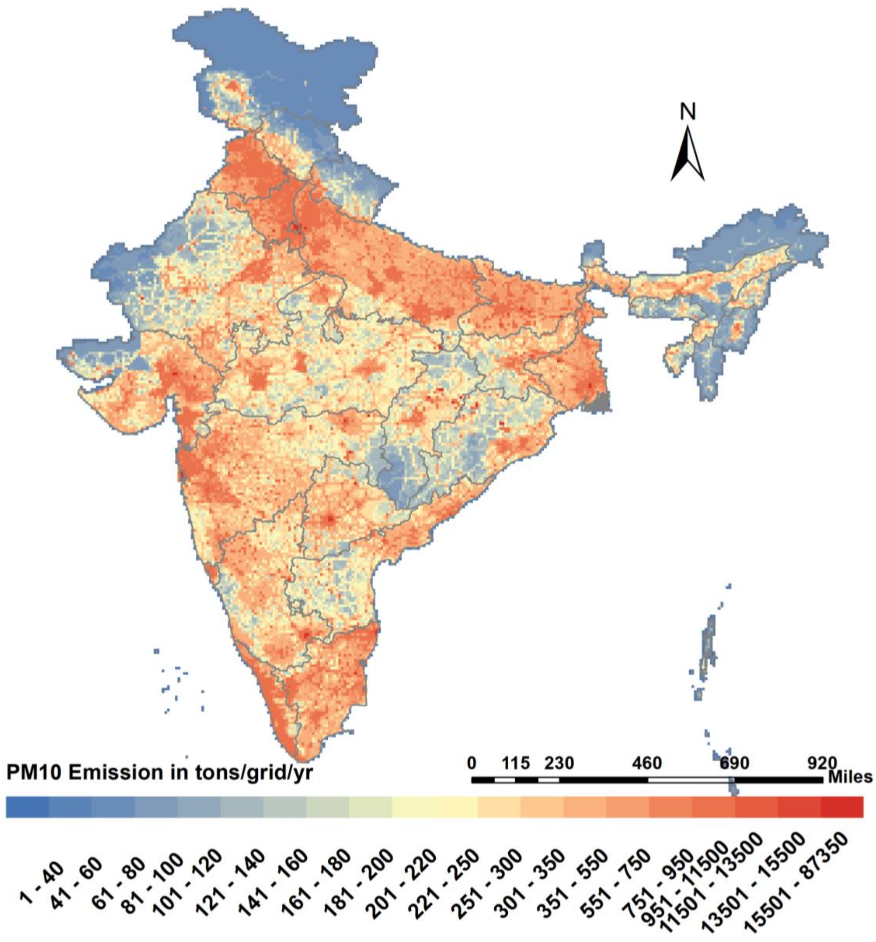

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635 **Fig. 3: Spatial map of gridded PM_{10} Emission in India**

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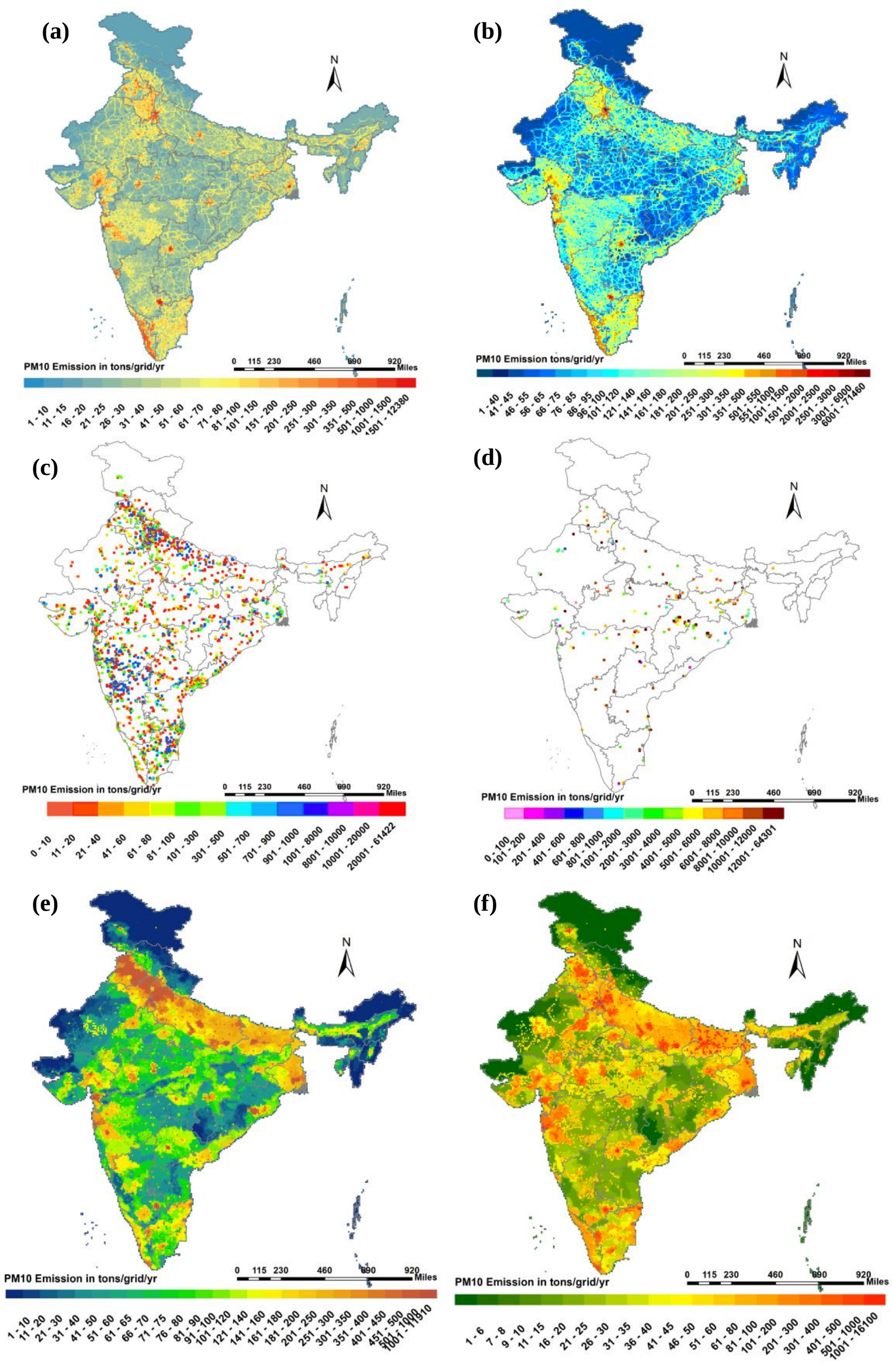

Fig.4: Sector-wise PM_{10} Emission: - (a) Transport (b) Windblown road dust (c) Industry (d) Thermal power plant (e) Residential (f) Other

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3.2 Relative contribution of different sectors:

We find that $PM_{2.5}$ and PM_{10}emissionis a pan-India problem with a regional character. The relative contribution of each individual sector to total $PM_{2.5}$ and PM_{10} emission is shown in the Fig.5. With respect to PM_{10}emission, the leading contributors involve windblown road dust with ~27.40%; residential as a whole ~23.08% which embodies several minor sectors like that of slum, household, street vendor, residue burning, cow-dung, and diesel set; followed by others with ~19.74% that incorporates minor sectors of municipal solid waste burning, municipal solid waste treatment plants, construction, brick kilns, incense sticks/mosquito coil/cigarette, and crematory; followed by transport ~10.25%; industry ~10.20% and thermal power plant with ~9.34%.

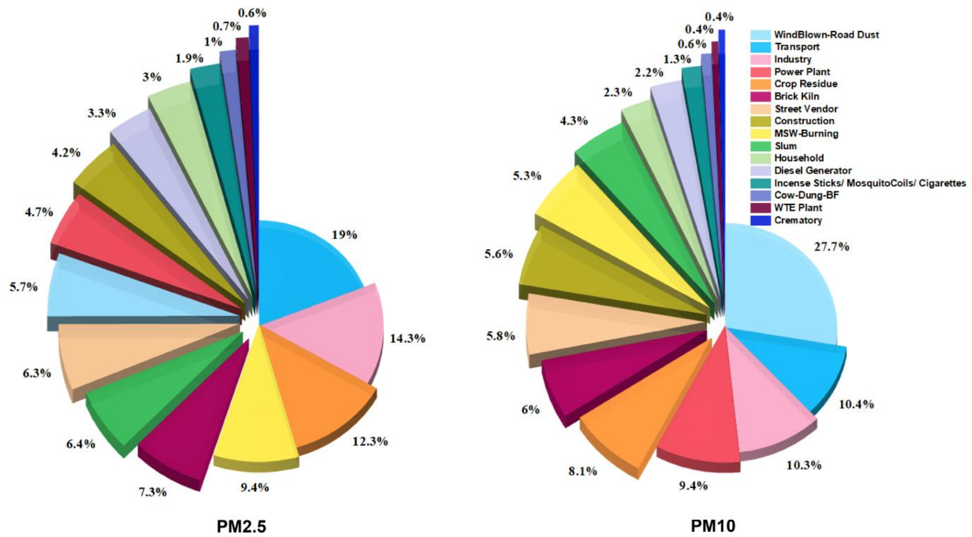

Fig.5: Relative contribution of different sectors to Total $PM_{2.5}$ andPM_{10} Emission in India

3.3 Inter-comparison with global inventory:

In this study, an inter-comparison of present new emission inventories of PM_{10} and $PM_{2.5}$ has been bone with existing emissions inventories of EDGAR-2015 (Crippa et al., 2019), MIX Asia-2010 (Li et al., 2017), INTEX-B-2006 (Zhang et al., 2009), and REAS-2015 (Ohara et al., 2007) (Fig. 6). This study provides estimates at provincial and/or national levels to assess the emissions at the source sector level. In present work, the major PM_{10} share is being held by windblown sector i.e., 4371.6 Gg/yr. There is large disparity, by a factor of 9, in transport

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emission between present and EDGAR emission. EDGAR estimation for the similar sector shows a value of 178.68 Gg/yr and does not show a good agreement. The residential (domestic) sector in the present work has the second largest PM_{10} emission i.e., 3682.41 Gg/yr. The sector justifies the significant number as it incorporates the sub sectors like slum, street vendors, diesel generators, crematorium, and incense sticks etc. The practice of use of raw coal, dung, wood as fuels for cooking and household activities significantly increases the indoor PM emission. Sub-sectoral variation is one of the keys for the residential sector across the inventories. The REAS-2015database does not have a defined estimate for the residential sector and there is a huge disparity between the recorded EDGAR-2015database and present emission estimations. Similarly, for the industry sector the REAS inventory shows an absolute high number (5010.4 Gg/yr), which is almost three times of the current work. The emission from road transport sector in the present work is estimated to be1635.41 Gg/yr, which has a significant deviation from the previous inventories in the order of 9 and 4 from EDGAR and REAS respectively. This deviation is due to inclusion of detailed information like category-wise age of vehicle and corresponding technological dynamic fuel-based emission factors for the most recent base year. Similarly, a huge discrepancy is also seen when compared to other global inventories of INTEX-B-2006 and MIX-Asia-2010 too. Moreover, this difference is absolutely due to the difference in base years and adopted emission factors. This work has taken account of all such country specific key factors appropriately to develop surface chemistry, and is therefore believed to be the most comprehensive, reliable, and updated one that can represent the real-time scenario perfectly.

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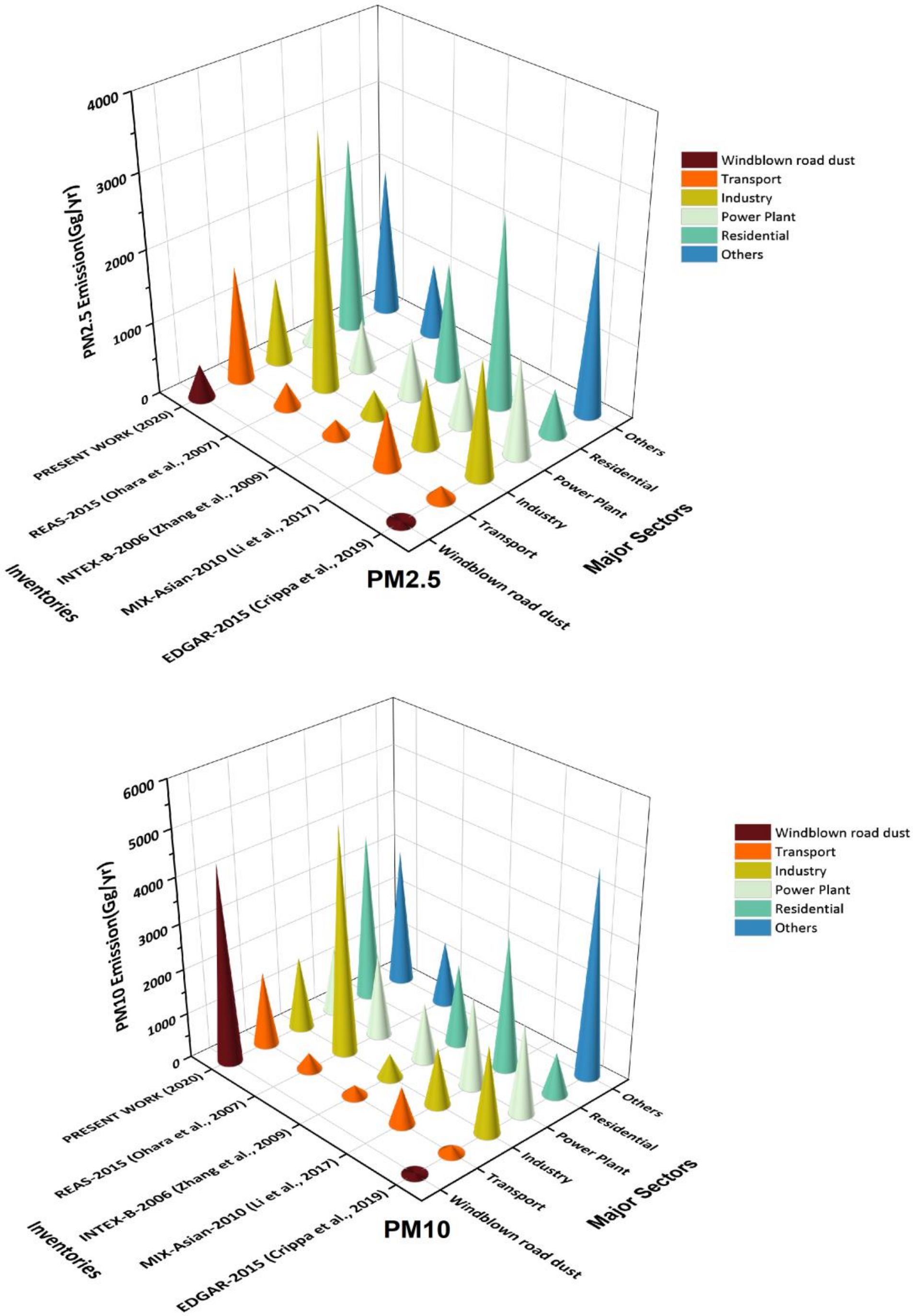

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682 **Fig. 6: Comparison with global inventories**

3.4 Uncertainty analysis:

Uncertainty assessment is sensitive piece of work and key to control measures. It analyses the uncertainty in input data such as activity data and emission factors, which are used to compile an inventory. An inventory do consider several assumptions due to missing data. The measured values may have several errors and the emission factors adopted might not be truly representative. Here, Monte Carlo analysis is adopted where the aim is fulfilled by incorporating the critical factors like activity data uncertainty and emission factor uncertainty. Firstly, the error propagation with respect to activity data and emission factor is calculated followed by combined uncertainty evaluated by considering the uncertainty percentage of both the emission factor as well as activity data for all the sectors. Then contribution to variance was determined from the combined uncertainty and summation of emission. As a result of which the total average percentage of uncertainty in the present study is estimated to be ±85.7 %. Other recent studies have reported uncertainty percentage ranges between ±120% to ±128% (Saikawa et al 2017, Kurokawa and Ohara 2019), i.e., markedly higher than in present work.

4. Data Availability:

The surface emission dataset can be accessed through the open-access data repository at https://doi.org/10.5281/zenodo.7885103 (Sahu et al., 2023).

5. Conclusion:

This works presents a comprehensive and highly detailed inventory of $PM_{2.5}$ and PM_{10} emissions in India in 2020. Elevated emission of $PM_{2.5}$ and PM_{10} is a common problem across India, with a regionally distinct characteristic, and is not limited to urban areas or megacities. In present inventory, windblown road dust with ~4371.6 Gg/yr is the dominating source of PM_{10} emissions, while transport and industry are the most important sources of $PM_{2.5}$. The vehicle-induced dust is a very complex process involving several parameters as discussed in the study where state of pavement, silt content on the road, vehicular weightage and vehicle speed are the major modulating factors throughout the country. The residential is emerged as the second largest sector influencing outdoor air. This residential sector with ~3682.41 Gg/yr incorporates agricultural residue burning (~1286.58 Gg/yr), street vendor (~919.15 Gg/yr) and slum (~675.46 Gg/yr) which are the important sources, making residential sector hit the second place. The road transport sector remains the third dominating sector with ~1635.41 Gg/yr of PM_{10} emission. The increase in vehicle fleet volume due to demand of personal vehicles and

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the flow of the aging vehicles are the major reasons for elevated road transport emissions. The spatial resolution of this study makes it suitable as input atmospheric and climate models of different resolution for studies of aerosol-induced climate and environmental effects. It is a promising and comprehensive piece of work developed at national scale. In addition to this, the developed dataset could be useful for air quality mitigation and control strategies across nation. Here we formulate a few recommendations for possible mitigation strategies: -

a) Discard of super-emitters (more than 15 yrs old vehicles) across the country and more than 10 yrs in all megacities. A shifting to cleaner fuel along with advanced technology with respect to vehicle type especially heavy commercial vehicles and commercial vehicles could be an effective abatement to transport emissions.
b) The vehicles of the surrounding districts or suburbs must also follow similar rules to control the emission load in and around the megacity.
c) Flexible working hours along with work from home culture has to be adopted in order to avoid traffic congestion in cities will reduce the tailpipe emission significantly.
d) Both the paved and unpaved roads must be well-maintained and regularly checked out for broken shoulders. Road shoulders if planted with grass beds to prevent scrapping of the silt load and its resuspension in the form of dust.
e) The usage of improvised public transport system must be promoted as the 2W, and commercial cars are the largest contributor to road dust resuspension.
f) Advanced technology based cleaner control devices must be used in the industrial smoke stacks. The control must be monitored and checked for efficiency in every year interval towards its maintenance.
g) Access to cleaner household energy for cooking activities, heating and lighting purposes should be made cost-friendly for its maximum usage and fuel adulteration must be monitored.
h) Improving the energy efficiency of residential buildings or apartments and encouraging making cities go green and compact would be resourceful.
i) Use of low-emission fuels or preferably renewable energy combustion free power sources such as solar, wind or hydro (co-generation of heat and power) would be helpful.
j) Utilization of crop waste could be used as an alternative to replacing incomplete combustion based on open burning in agricultural lands and demand for coal may reduce could possibly reduce the emission load.

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k) Recycling and reuse or re-processing of the waste materials into useful products as well as improving or encouraging the biological waste treatment methods. Allowing cost effective alternatives to the open burning/incineration of waste with strict emission controls are vital.

Author contributions:

Saroj Kumar Sahu (SKS) conceived the present idea and analyzed the data and Poonam Mangaraj (PM) wrote the whole paper. Gufran Beig (GB) provided useful discussion. Marianne T. Lund (MTL) and Bjørn Hallvard Samset (BHS) both helped in analyzing the data and suggested a conclusion. Pallavi Sahoo (PS) analyzed the data, Ashirbad Mishra (AM) helped in plotting the scientific data.

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The contact author has declared that none of the authors has any competing interests.

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