Supplementary File

Reporting of Gridded (0.1°X0.1°) Methane Emission Data for India to Redefine Global Climate Studies

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Emission estimation:

The total methane emission budget is the summation of sectoral methane emission which is calculated by using equation 1.

$$E_{\mathrm{CH4}} = \sum_{Sources} AD \times EF \qquad \text{Eq (1)}$$

Where E_{CH4} is the emission of CH_4 from a sector, AD is the activity data, and EF is the emission factor corresponding to that particular source category.

Livestock: -

The CH_4 emissions from livestock are broadly classified into two categories, i.e., enteric fermentation and manure management. The emission from enteric fermentation comes from the digestive process of the ruminants, which varies with age, gender, species, temperature, living conditions, and grazing pattern. This study incorporates 10 livestock species, which are further discretized according to age and productivity. The population under each category is taken from the 20th livestock Census-2019, a national-level livestock population survey, which is extrapolated for the year 2023, accounting for 548.7 million livestock and 2.7 billion poultry [DAHD, 2019]. India, home to more than half of the world's livestock, possesses the largest bovine population globally. The accumulation of livestock population is predominantly found in Northern India, Indo-Gangetic Plain (IGP), and Decan Plateau Regions (DPR). To take accountability for the CH_4 emission, a comprehensive species-wise analysis was carried out at the district-level and further defined at the village-level. The emission for individual categories is calculated as per equation 2.

$$E_{LS}(\mathrm{Tg/yr}) = \sum_{Species} \frac{P_{LS}}{10^9} \times EF_{LS} \qquad \text{Eq (2)}$$

Where E_{LS} is the emissions from the livestock sector i.e., from both enteric fermentation and manure management, Tg/yr is Teragram per year (10^{12} grams/year), P_{LS} is the population of livestock under each category, and EF_{LS} is a distinct emission factor for individual categories' enteric fermentation and manure management.

Agricultural Practices: -

Vegetative agricultural practices, particularly rice and sugarcane cropping, are one of the leading sources of CH_4 emissions globally [Saunois et al., 2020]. India, which bears a suitable agro-climatic zone, has emerged as the second-largest producer of rice and sugarcane in the world [USDA, 2024]. These crops are cultured in the flooded water regime, which lead to CH_4 emissions due to anaerobic disintegration of organic materials in the waterlogged soil. This CH_4 diffuses into the atmosphere through plants. The emission is largely influenced by various other factors like water availability, cropping pattern, weather, soil structure, fertilizer usage, etc [Saunois et al., 2020]. The geographic distribution of extensive cropping patterns increases the emission of CH_4 in the rice belt (i.e., IGP, Northeastern states, Eastern coastal states). The crop fields in these areas are classified as rainfed, irrigated, deepwater, and upland areas. The total CH_4 budget is the resultant of emissions from all the water regimes (WR) for rice and sugarcane crops that can be formulated as:

$$E_C\ (\mathrm{Tg/yr}) = \sum_{WR} \frac{A_C}{10^9} \times PC_{WR} \times EF_{WR} \qquad \text{Eq (3)}$$

Where E_C is the emission from the crop field (i.e., rice or sugarcane), A_C is total area of cropping, PC_{WR} is percentage (%) of a particular water regime and EF_{WR} is the CH4 emission factor for that particular water regime.

Waste management: -

Solid Waste Burning: -

The waste management sector ranks as the third largest contributor to global indirect GHGs emissions [USEPA, 2012]. India is a global production hub and emerging economy, where waste generation and its management have emerged as the biggest sustainable burdens recently [Mangaraj et al., 2022a, 2022b, 2024a, 2024b]. This study quantifies the emission of CH_4 from waste sources that include municipal solid waste (MSW) landfilling and open burning, along with residential and industrial wastewater treatment, by adopting the IPCC tier II/III bottom-up approach. Methane emissions from waste management primarily result from the anaerobic decomposition of organic matter in both solid waste and wastewater. These emissions are closely tied to the population density and living standards of the region, with higher emissions typically observed in cities with populations exceeding 0.1 million. The current estimation is based on the per capita solid waste generation in different living conditions like cities, rural areas, etc., which is fragmented according to Tier I, II and III cities and rural India. As per CPCB's annual report on Solid waste Management (2021), 30% of waste is burned openly, which emits CH_4 into the atmosphere [CPCB, 2021]. We calculated the same using equation 4.

$$E_{MSWB}(\mathrm{Tg/yr}) = \left\{\frac{\sum P_{i,j,k} \times MSW_{i,j,k}}{10^{12}}\right\} \times PC_B \times EF_B \qquad Eq(4)$$

Where E_{MSWB} is the emission from MSW burning, i, j, k is the types of cities (tier I/II/III) or rural, P is the population in that region, MSW is solid waste generation per capita, PC_B is the percentage of waste burnt, EF_B is CH4 emission factor (g/kg) for waste burning.

Solid Waste Landfilling: -

In landfills, CH4 is emitted due to the anaerobic disintegration of decomposed waste. Open dumping of solid wastes is the emerging concern across the Indian subcontinent. Nearly one-third of the total MSW generation is openly dumped as per the CPCB report (2021). Besides this, landfilling and composting account for ~20% and 7.5% respectively, which is responsible for CH4 emissions through methanogenesis [CPCB, 2021]. The CH4 emission from landfilling is calculated considering all three waste management practices in this study, which can be formulated as equation 5.

$$E_{MSWL}(\mathrm{Tg/yr}) = \left\{\frac{\sum P_{i,j,k} \times MSW_{i,j,k}}{10^{12}}\right\} \times \sum_{O,L,C} PC \times MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12} - R\right) \times (1 - OX) \qquad \mathrm{Eq}(5)$$

Where E_{MSWL} is the emission from MSW landfilling, i, j, k is the types of cities (tier I/II/III) or rural, P is the population in that region, MSW is solid waste generation per capita, PC is the percentage of waste managed under various categories, O is open dumping, L is landfilling and C is composting,

MCF is the Methane correction factor, considered 0.4,
DOC is the Degradable organic carbon, considered 0.114,
DOC_F is the Dissimilated fill gas, considered 0.77,
F is the Fraction of CH4 gas, considered 0.5,
R is the recovered methane gas, considered 0,
OX is the oxidation factor, considered 0.

Wastewater Management: -

Similarly, CH4 is emitted from wastewater in landfilling sites due to the anaerobic decomposition of organic matter. So, the governing factor in potential CH4 generation is the amount of degradable organic matter present in the wastewater. The emission of CH4 from wastewater is divided into two categories: residential and industrial wastewater, calculated by equation 6.

$$E_{WW}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{R,I} WW_T \times BOD \times MCF \times B_O \times \frac{365}{10^9} \qquad \mathrm{Eq}(6)$$

Where E_{WW} is the emission from wastewater, R and I denote residential and industrial wastewater, WW_T is the wastewater treated at the treatment plant (l/day), BOD is the total organic waste load (mg/l), MCF is the Methane correction factor, considered 0.5, B_O is the maximum methane-producing capacity of raw sewage (kg CH4/ kg BOD), considered 0.6.

Forest Fires: -

Forest fire events are disrupting the terrestrial ecosystem globally, making it a significant contributor to air pollution and climate change. With a total forest area of ~80.9 million ha, India ranks 10th in the world and ranks third in net gain in forest cover in the last decade [MoF, 2023]. However, ~212249 forest fire incidents were observed in 2022, affecting ~3.85 million ha of forest area in the country [MoEFCC, 2023]. CH4 is emitted from biomass burning due to incomplete combustion conditions, and the rate of emission is modulated by the type of biomass and the biomass load. Thus, the amount of CH4 emitted in different forest fire events is calculated according to the forest type using equation 7.

$$E_{FF}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{FT} \frac{A_{FF}}{10^{12}} \times PC \times BL \times FB \times EF \qquad \mathrm{Eq}(7)$$

Where E_{FF} is the emission from forest fire, FT is forest type burnt, A_{FF} is the total area lost due to forest fire, PC is the percentage of forest type burnt, BL is the biomass loading of the forest type, FB is the fraction of biomass burnt, EF is the emission factor for biomass burnt of each forest type.

Crop Residue Burning: -

Crop residue burning is a pressing challenge in the Northern, Northeastern and Indo-Gangetic states of India [Sahu et al., 2021]. To prepare the crop field for next cropping, farmers deliberately burn the residues of the last crop. This traditional slash-and-burn approach to crop residues worsens the surrounding air quality by emitting CH_4. The amount of CH_4 emissions from the crop residue burning depends on the type of crop and the amount of dry matter present in the residue. We have taken a number of major crops, including rice, wheat, cotton, sugarcane, pulses, etc., for the estimation of CH_4 emissions, which can be formulated as equation 8.

$$E_{CRB}(\mathrm{Tg/yr}) = \sum_{CT} \frac{P}{10^{12}} \times RPR \times DMF \times FB \times EF \qquad \mathrm{Eq(8)}$$

Where E_{CRB} is the emission from crop residue burning, CT is the crop type, P is the production of that crop, RPR is the residue to production ratio of that crop, DMF is the dry matter fraction in the residues, FB is the fraction of residue burnt, and EF is the emission factor of residue burning for each crop type.

Cooking Activity: -

India is home to 1.4 billion people, and they use solid biofuel extensively in cooking activities. The inaccessibility to cleaner fuel makes this sector a significant contributor to air pollution in the country. Usage of wood, coal, crop residues, and cow dung cake, is still predominantly used as cooking fuel in the lower-income categories. With the enactment of the Pradhan Mantri Ujjwala Scheme, beneficiaries are shifting toward LPG consumption more rapidly. The percentage share of cooking fuel characteristics in different household types is taken from the 78th NSS Report 2020-21 [MoSPI, 2023]. Similarly, commercial cooking activities like restaurants, hotels, and street vendors are also taken into account in the emission estimation. Their per-day fuel type and consumption data were collected from previously published city-specific studies [Mangaraj et al., 2022a, 2022b, 2024a, 2024b, Štimac et al., 2023, Majumdar, 2013]. The emissions from cooking activities are the summation of emissions from both the residential and commercial sources. It is calculated as per equation 9.

$$E_{HH}(\mathrm{Tg/yr}) = \sum_{R,S,U} \sum_{C,W,L} T_{HH} \times PC_{HH} \times CF \times EF \times \frac{12}{10^{12}} \qquad \mathrm{Eq(9)}$$

Where E_{Cook} is the emission from cooking activities, R, S, and U are for rural, slum and urban region emission, C,W,L are for fuel type like coal, wood, and LPG, etc., T_{HH} is the total households under that categories, PC_{HH} is the percentage of households using a particular fuel for cooking, CF is the monthly consumption of fuel, EF is the emission factor of the that particular fuel.

Transportation: -

Methane emissions from the transportation sector are minimal but occur due to the incomplete combustion of various fossil fuels. In recent years, the number of vehicles in India has increased significantly, reaching ~326 million in 2023 [MoRTH, 2023]. This study takes into account an array of vehicle types, including two-wheelers, three-wheelers, personal and commercial cars, buses, and heavy and light-duty vehicles, as well as other miscellaneous vehicles. Additionally, it considers different fuel types used by these vehicles, such as gasoline, compressed natural gas (CNG), petrol, and diesel. The total emissions of CH4 from the transport sector are estimated using equation 10.

$$E_{TRN}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{VT} \sum_{AGE} N \times PC_{OR} \times VKT \times EF \times \frac{365}{10^{12}} \qquad \mathrm{Eq(10)}$$

Where E_{TRN} is the emission from transport sector, VT is the vehicle types, AGE is the vehicle age categories (i.e., 5, 10, and 15 years), N is the number of registered vehicles, PC_{OR} is the percentage of vehicles plying on road, VKT is the distance travel by the vehicle in kilometer in a day, EF is the emission factor of the fuel used.

Coal Mining: -

A significant portion of anthropogenic methane is emitted during mining operations and predominantly originates from ventilation shafts, where substantial volumes of air are introduced into the mines to maintain the CH4 mixing ratio below 0.5%, thereby preventing accidental ignition.[2]

India, with a coal reserve of ~344 billion tonnes, ranks as the fifth-largest country globally in terms of coal deposits and the second-largest in coal production [MoC, 2020]. The monitoring of all coal mines within India falls under the jurisdiction of the Directorate General of Mine Safety. Mines across various states are categorized broadly by surface and underground coal mines, which are further disaggregated by degrees of gassiness (Degree I, II, and III) rather than by size. The total CH4 emission from coal mining activities can be calculated from equation 11.

$$E_{CM} = \sum_{MT} \frac{P_C}{10^3} \times EF \times CF \qquad \text{Eq(11)}$$

Where E_{CM} is the emission from coal mining, MT is the mine type, P_C is the Production of coal from each mine (tonne), EF is the methane emission factor (m^3/tonne), CF is the conversion factor (0.67×10^{-6} Gg/m^3)

Oil and Gas Production and Refining

Though India has extremely limited oil and natural gas reserves, the refineries do contribute significantly to CH4 emissions from this sector. As natural gases are primarily composed of CH4, it diffuses into the atmosphere during the extraction and refining process. The estimated CH4 emissions from this sector can be formulated as equation 12.

$$E_{OIL}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{E,R} \frac{V}{10^{12}} \times EF \qquad \text{Eq(12)}$$

Where E_{OIL} is the emission from the oil and natural gas sector, E, and R are the extraction, flaring and refining of oil and natural gas, V is the volume of extraction, flaring and refining of oil and natural gas and EF is the CH4 emission factor associated in each process.

Thermal Power Plants

In India, coal-based power plants satisfy approximately half of the national energy demand. As of 2022, the total installed capacity of thermal power plants is approximately 237,268.9 MW [CEA, 2023]. This sector consumes around 709.86 million tonnes of coal and 38.76 million tonnes of lignite [ESI, 2023]. The extensive use of coal for energy production renders this sector unsustainable and significantly influences regional air quality. Methane emissions resulting from the combustion of these fuels are quantified based on the fuel consumption data of individual plants as per equation 13.

$$E_{TPP}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{C,L} \frac{F}{10^{12}} \times EF \qquad \mathrm{Eq(13)}$$

Where E_{TPP} is the emission from thermal power plants, C, L are for fuel types like coal or lignite, F is the amount of fuel used (kg), and EF is the CH_4 emission factor of that particular fuel.

Brick Kilns

India holds the second position globally in brick production, with an annual average output of approximately 250 billion bricks produced by 144,000 operational brick kilns [Rajarathnam et al., 2014, Eil et al., 2020]. This sector is responsible for the annual consumption of nearly 41 million tonnes of coal and 31 million tonnes of biomass [Tibrewal et al., 2023]. The methane emissions from this sector are determined by using equation 13 based on the consumption of coal and biomass by the brick kilns.

Crematories

The traditional pyre systems commonly utilize wood for combustion, which may also contribute to CH_4 emissions. According to the World Bank (2023), India's current crude death rate (CDR) is 9 [World Bank, 2023]. Approximately 80% of the population, or around 1.13 billion Hindus, practice the traditional pyre cremation predominantly [Census, 2011]. It is estimated that there are about 10.2 million deaths among the Hindu community, with nearly 10% of these bodies being cremated using electric methods, while the remaining 90% are traditionally burned. The cremation of a single body typically requires around 550 kg of wood [Mangaraj et al., 2022a, 2022b, Sahu et al., 2023, Chakrabarty et al., 2013]. The CH_4 emissions from this sector can be calculated by multiplying the number of deaths, the wood consumption per individual, and the corresponding emission rate as per equation 14.

$$E_{CRM}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \frac{P_T}{10^{12}} \times PC_H \times MR \times PC_{TB} \times F_W \qquad \mathrm{Eq(14)}$$

Where E_{CRM} is the emission from crematories, P_T is the total population of India, PC_H is the percentage of Hindu population, considered 80%, MR is the mortality rate, considered 9 in 1000, PC_{TB} is the percentage of traditional burning of deceased, considered 90%, F_W is the amount of fuel wood consumption per individual.

Wetlands

Wetlands are generally defined as ecosystems characterized by waterlogged or saturated soils or peats, where anaerobic conditions promote methane production [Anderson et al., 2010]. This study encompasses all inland freshwater sources, such as ponds, rivers, and lakes, as well as coastal brackish water sources and coastal vegetative ecosystems, including mangroves. In India, 4.6% of the land area is covered by natural and artificial wetlands, featuring an extensive coastal length of approximately 7,500 km and around 5,000 km^2 of mangrove forests. These regions are predominant in methane emission. The three principal factors influencing methane production in wetlands are the spatial and temporal extent of anoxia (associated with water saturation), temperature, and substrate availability [Wania et al., 2010, Whalen et al., 2005]. Temperature variability and geographical location play a significant role in determining the emission profile. To assess these factors, this study utilized temperature data from the Indian Meteorological Department's annual gridded dataset (https://www.imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html), along with productivity factors sourced from various published scientific literature [Garg et al., 2005]. Taking into account the above factors, CH4 emission can be derived from equation 15.

$$E_{WL}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{WT} \frac{A}{10^{12}} \times MF \times TF \times PF \qquad \mathrm{Eq}(15)$$

Where E_{WL} is the emission from the wetland, WT is the wetland types, A is the area of the wetland, MF is the observed methane emission flux, TF is the temperature factor = $e^{0.334(T-23)}/1+ e^{0.334(T-23)}$, where T is the surface temperature, PF is the productivity factor, considered 0.25 for high-altitude wetlands, 0.5 for the rest of India, and 1 for mangroves [Garg et al., 2005].

Termites

Termites, classified under the infraorder Isoptera, predominantly inhabit tropical and subtropical latitudes [Abe et al., 2000]. Methane emissions from termites are produced by symbiotic microorganisms within their digestive systems. The estimation of CH4 emissions from termite nests employs the methodology developed by Sanderson M.G. (1996), which calculates emissions based on termite biomass per unit area of forest and the CH4 flux per unit termite biomass which can be formulated in equation 16.

$$E_{TRM}\left(\frac{\mathrm{Tg}}{\mathrm{yr}}\right) = \sum_{FT} A \times TB \times MF \times \frac{24 \times 365}{10^{12}} \qquad \mathrm{Eq}(16)$$

Where E_{TRM} is the emission from termites, FT is the forest type, A is the area of that forest type, TB is the termite biomass per unit forest area, and MF is the CH4 emission flux per unit termite biomass per hour.

Table S1: Source of Sector-specific activity data details

Sl. No.	IPCC 2006 Code	Sector	Methodology Adopted	Sources
1	3.A.1	Livestock Enteric Fermentation	Tier II	Ministry of Fisheries, Animal Husbandry & Dairying https://dahd.nic.in/
	3.A.2	Livestock Manure Management		
2	3.B.4	Wetland	Tier II	Wetlands of India Portal https://indianwetlands.in/
3	3.C.7	Rice & Sugarcane Cultivation	Tier II	Department of Agriculture & Farmers Welfare https://agriwelfare.gov.in/
4	1.B.1.a	Coal Mine	Tier II	Ministry of Coal https://coal.nic.in/
5	4.C	Municipal Solid Waste Burning	Tier III	Central Pollution Control Board https://cpcb.nic.in/
	4.A	Municipal Solid Waste Landfilling		
6	4.D.1	Domestic Wastewater Treatment	Tier II	Central Pollution Control Board https://cpcb.nic.in/
	4.D.2	Industrial Wastewater Treatment		

7	3.C.1.a	Forest Fire	Tier II	Ministry of Environment, Forest and Climate Change https://moef.gov.in/
8	3.C.1.b	Crop Residue Burning	Tier II	Ministry of Agriculture & Farmers' Welfare https://agricoop.gov.in/ Ministry of Statistics and Programme Implementation https://www.mospi.gov.in/
9	1.B.2.a	Oil production and Refining	Tier II	Ministry of Petroleum and Natural Gas https://petroleum.nic.in/
	1.B.2.b	Gas Production		
10	1.A.4.b	Residential and Slum	Tier II	Census of India https://censusindia.gov.in/census.website/ Ministry of Housing and Urban Affairs https://mohua.gov.in/ UN World Urbanization Prospects https://population.un.org/wup/
11	1.A.4.a	Street vendor, Hotel & Restaurant	Tier II	India's Street Vending (Protection of Livelihood and Regulation of Street Vending) Act https://mohua.gov.in/upload/uploadfiles/files/StreetVendorAct2014
12	1.A.3.b	Transport	Tier II	Ministry of Road Transport & Highway https://morth.nic.in/ Ministry of Statistics and Programme Implementation https://www.mospi.gov.in/
13	1.A.1	Thermal Power Plant	Tier II	Ministry of Power https://powermin.gov.in/ Central Electricity Authority https://cea.nic.in/?lang=en
14	1.B.1	Crematorium	Tier II	Ministry of Home Affairs https://www.mha.gov.in/en SAFAR- Delhi (2018), Pune (2020)
15	1.B.1	Brick Kiln	Tier II	Central Pollution Control Board https://cpcb.nic.in/ Seay et al., (2021) https://doi.org/10.1088/2515-7620/ac0a66 Rajarathnam et al., (2014) https://doi.org/10.1016/j.atmosenv.2014.08.075
16		Termite	Tier I	Ministry of Environment, Forest and Climate Change https://moef.gov.in/

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Table S2: Emission Factor for the Livestock Sector

Category	Sub category		Present Study	Other Studies	Present Study	Other Studies	Reference
			Enteric Fermentation		Manure Management		
Dairy cattle	Indigenous	kg/head	34	28-46	4.25	3.5-5	[NATCOM, 2004, 2012, IPCC, 2006, Garg et al., 2011, Samal et al., 2024]
	Crossbred		46	43-49	4.4	3.8-5	
Non-dairy cattle (Indigenous)	0-1 year		13.3	9-17	1.6	1.2-2	
	1-3 year		26	23-30	2.4	2.8-2	
	Adult		31.3	25-37	2.45	2.9-2	
Non-dairy cattle (Crossbred)	0-1 year		13.3	11-17	1.55	1.1-2	
	1-2 ½ year		27.3	25-31	2.15	2.3-2	
	Adult		32	25-38	2.25	2.5-2	
Dairy buffalo			49	42-55	4.7	4.4-5	
Non-dairy (Buffalos)	0-1 year		14.3	8-23	3.4	1.8-5	
	1-3 year		35.3	22-55	4.2	3.4-5	
	Adult		49.3	44-55	4.5	4-5	
Sheep			4.3	4-5	0.26	0.18-3	
Goat			4	3-5	0.19	0.18-0.2	
Horses & Ponies			12.04	6-18	1.6	1.6	
Donkeys			8.04	6-10	0.93	0.9-0.96	
Camels			26.04	6-46	1.78	1.6-1.96	
Pigs			3.54	1-6	4.185	4-4.37	

Chicken			0.015	0.015	[Zhou et al., 2007]
Ducks			0.01	0.01	
Geese			0.02	0.02	
Turkeys			0.11	0.11	

Table S3: Country-specific emission factor used for various sectors

Category	Subcategory	Unit	Present Study	Other Studies	Reference
(a) Rice and Sugarcane					
Irrigated	Continuous flooding	kg/ha	168	162-174	[NATCOM, 2004, 2012, Garg et al., 2011, Bhatia et al., 2013]
	Single aeration		66	66	
	Multiple aeration		19	18-21	
Rain-fed	Flood-prone		190	190	
	Drought-prone		68	66-70	
Deepwater			190	190	
Upland			0	0	
(b) Wetland					
Freshwater	East, West and Central	mg/m2/hr	15.42	6.05-24.79	[Shaher et al., 2018]

	North and IGP		18.69	3.33-68	
	Northeast		7.07	4.05-10.4	
	South		11.36	3.27-21.56	
Saline water			7.8	6.52-9.30	
Mangrove*	East	mg/m2/d	1.09-156.48		[Shaher et al., 2018, Chauhan et al., 2008]
	West		10.15-177.11		
	South		10.15-177.12		

(c) Waste Management				
Solid Waste Open Burning		g/kg	4.59	[Chaudhary et al., 2021]
Solid Waste Land Filling	Methane correction factor (MCF)		0.4	[Singh et al., 2018]
	Degradable organic carbon (DOC)		0.114	
	Dissimilated fill gas (DOCf)		0.77	
	Fraction of methane gas (F)		0.5	

Wastewater Treatment	Total Organic Waste Load (BOD)	mg/l	205	[Singh et al., 2017, Karthik et al., 2011]
	Methane correction factor (MCF)		0.5	
	Maximum Methane Production Potential (Bo)	kg CH4/ kg BOD	0.6	

(d) Oil & Gas				
Oil production	Fugitive (onshore)	g/kg	36.3	[Garg et al., 2011]
	Fugitive (offshore)		0.00071	
	Crude oil Processing		3.91	
Natural Gas	Production	g/SCM	12.19	
	Flaring		0.00088	

(e) Coal Mining				
Surface Mining		m3/tonne	1.18	[Singh et al., 2016]
Underground Mining	Degree—I		2.91	

	Degree—II		13.08	
	Degree—III		23.68	
Thermal Power Plant	Coal	g/kg	0.15	[Pandey et al., 2014, Sadavarte et al., 2014]
	Lignite		0.3	
(f) Crop Residue Burning				
Rice		g/kg	9.59	[Khaiwal et al., 2019, Sahai et al., 2007, Kanabkaew et al., 2010, Li et al., 2022]
Wheat			3.55	
Maize			4.4	
Coarse cereal (Sorghum)			4.4	
Jute			4.56	
Cotton			4.56	
Sugarcane			0.4	

Oilseed (Rapeseed)		3.5	
Pulses (combined crop)		4.56	
(g) Forest Fire			
Coniferous		5.68	
Tropical moist deciduous		5.07	
Tropical dry deciduous		5.07	
Wet semi-evergreen	g/kg	5.96	[Akagi et al., 2011]
Temperate		3.92	
Shrubland		1.94	
Grassland		1.94	
(h) Cooking Activities			
Charcoal	g/kg	7.9	

Dung		7.2	[IPCC, 2006, Garg et al., 2011, Pandey et al., 2014, Gurjar et al., 2004]
Wood		6.4	
LPG		0.354	
Kerosene	g/l	0.7	
(i) Brick Kiln			
Coal	g/kg	0.15	[Garg et al., 2011, Pandey et al., 2014, Gurjar et al., 2004]
Biomass		6.4	
(j) Termite			
Very dense forest	g/g termite mass/hr	6.16	[Sanderson et al., 1996, European Commission, 2018]
Moderately dense forest		1.77	
Open forest		7	
Scrub		1.7	

Agricultural land	3.9	

Table 4: Emission Factor for the Transport Sector

Category	Subcategory			Reference
	5yr	10yr	15yr	
2W (Gasoline)	0.0417	0.0558	0.18	[Gurjar et al., 2004]
3W (CNG)	0.4	0.45	0.5	
3W (Gasoline)	0.014	0.021	0.18	
Bus (CNG)	1.2216	1.25	1.25	
Buses (Diesel)	0.0006	0.0007	0.09	
P Cars (Gasoline)	0.0107	0.0107	0.0134	
C Cars (CNG)	0.43	0.43	0.45	
C Cars (Diesel)	0.0003	0.0003	0.0004	
HCV (Diesel)	0.0031	0.0031	0.0031	
LCV (Diesel)	0.0006	0.0006	0.0007	
MSLV (Diesel)	0.09	0.09	0.09	

Uncertainty Estimation

The evaluation of uncertainty serves as a crucial parameter for EI development, which are foundational in establishing control measures. The initial stage of this analysis entails a thorough examination of the uncertainties inherent in both activity data and emission factors (EFs). Additionally, it is acknowledged that the selected emission factors may not adequately represent the current circumstances. To address this, uncertainty calculations have been conducted using both linear error propagation and the Monte Carlo simulation method, in accordance with IPCC guidelines. The detailed methodologies of uncertainty estimation through the above methods are presented in our previous studies [Mangaraj et al., 2024a, 2024b, Samal et al., 2024, Sahu et al., 2024, Sahoo et al., 2024]. All the essential statistical computations are performed in the IBM SPSS 24.0 software (https://www.ibm.com/spss).

GIS-based spatial allocation of emissions:

The spatial distribution of emissions is a complex task in terms of analysis and modeling. Geographic Information Systems (GIS) possess the capability to organize spatially heterogeneous data layers. Each emission dataset is aligned with a gridded cell layout to ensure accurate source data aggregation by consolidating control points within each cell. The geographical region of India encompasses 785 districts and is disaggregated into 30,185 grid cells, each with a resolution of 0.1° x 0.1° using ESRI ArcGIS 10.6 (https://www.esri.com/en-us/home). The gridded emission map is developed through a GIS-based statistical approach, wherein source-specific emission layers (including livestock, wetlands, crop fields, transportation, residential cooking, municipal solid waste, power plants, etc.) are created utilizing spatial information on sector specific activity data or fuel used. The resultant emissions are then organized as thematic layers. This methodology has been extensively employed in emission inventory development [Mangaraj et al., 2024a, 2024b, Sahu et al., 2021, Sahu et al., 2024, Sahoo et al., 2024].

As emissions from various sectors are consolidated to form the total emissions within the gridded cells, they are systematically arranged in the form of thematic layers for each sector type, facilitating individual analysis. The preparation of sectoral emission layers necessitates geospatial data, including details about India's road networks, geographic areas, and population. Livestock emissions are allocated to the grid cells corresponding to the livestock population and available pastureland. Emissions from rice and sugarcane crop fields are distributed according to district-level cropping areas, which are then integrated with spatially resolved agricultural land for gridded emission distribution. Wetland CH4 emissions are allocated based on the presence of water bodies for inland wetlands, as accessed from Vedas SAC, ISRO wetland atlas (https://vedas.sac.gov.in/en/National_Wetland_Inventory_and_Assessment_(NWIA)_Atlas.html), and the shoreline for coastal wetlands. Similarly, emissions from mangroves are distributed according to the availability of mangrove forest areas.

India's transportation sector encompasses an extensive road network of approximately 6.67 million km [MoRTH, 2023]. District-level emissions are computed and distributed over various road types based on vehicle types and its driving patterns. Emissions over dense road networks, such as national highways, state highways, and major and minor roads connecting industrial zones, are mapped to the gridded layer to determine transport-related emissions according to the relative contribution of each road type. Similarly, emissions from large-scale coal-based thermal power plants are allocated based on the locations, installed capacity, and fuel consumption patterns of approximately 201 plants [CEA, 2023].

Village-level data, such as population and agricultural land information, is utilized to enhance the spatial allocation of emissions from sectors including residential cooking, slums, street vendors, crematories, municipal solid waste burning, and livestock. This data aids in accurately distributing emissions based on urban and rural population patterns and fuel utilization. The spatial positioning of brick kilns, coal mines, oil and gas refineries, and wastewater treatment plants throughout India presents a formidable challenge due to the lack of readily available robust pre-constituted data. Therefore, identifying the precise locations of these sources was accomplished using Google Earth Pro, followed by geo-referencing based on feature size and texture patterns.

For forest fires and crop residue burning, the methods for extracting burned areas for emissions calculations are not well-documented. Accurate burned area estimates are particularly challenging to extract in forest and cropland areas. Therefore, information such as ground fuel loading, combustion efficiency, emission factors, and satellite-ground data integration methods, including the use of NASA FIRMS monthly active fire counts from MODIS-C6 and VIIRS for the required base year (https://firms.modaps.eosdis.nasa.gov/active_fire/#firms-shapefile), was adopted to calculate the gridded emission load over the Indian subcontinent. Emissions from termites are distributed according to the areas of various forest types. The grids associated with forest areas receive the respective emissions based on the incidence area. The generated data with precise spatial locations forms the foundation for the spatial allocation of emissions across each sector.

Table S5: State-wise relative emission of top 3 dominating sources and districts

States	Emission Share (%)	Top 3 Dominating Sectors			Top 3 Dominating Districts		
		1st	2nd	3rd	1st	2nd	3rd
Uttar Pradesh	10.82%	Livestock	Crop Field	MSW	Kheri	Allahabad	Sitapur
Gujarat	9.39%	Wetland	Livestock	Oil & Gas	Kachchh	Jamnagar	Ahmadabad
Maharashtra	8.65%	Wetland	Livestock	Crop Field	Mumbai Suburban	Pune	Ahmadnagar
Madhya Pradesh	6.52%	Livestock	Crop Field	Wetland	Singrauli	Sagar	Satna
West Bengal	6.25%	Livestock	Crop Field	Wetland	South 24 Parganas	Barddhaman	Paschim Medinipur
Andhra Pradesh	6.21%	Wetland	Livestock	Crop Field	SPS Nellore	East Godavari	Guntur
Odisha	5.72%	Wetland	Livestock	Crop Field	Puri	Anugul	Sundargarh
Rajasthan	5.19%	Livestock	Oil & Gas	MSW	Nagaur	Jaipur	Jodhpur
Karnataka	5.09%	Wetland	Livestock	Crop Field	Belgaum	Bangalore	Dakshina Kannada
Bihar	4.80%	Livestock	Crop Field	MSW	Purba Champaran	Madhubani	Rohtas
Telangana	4.54%	Wetland	Livestock	Crop Field	Nalgonda	Karimnagar	Mahbubnagar
Tamil Nadu	4.39%	Wetland	Livestock	Crop Field	Thiruvallur	Thiruvarur	Viluppuram
Chhattisgarh	3.48%	Livestock	Crop Field	Coal Mine	Korba	Baloda Bazar	Rajnandgaon
Assam	2.91%	Livestock	Oil & Gas	Crop Field	Tinsukia	Dibrugarh	Karbi Anglong
Andaman & Nicobar Islands	2.82%	Wetland	Livestock	MSW	North & Middle Andaman	South Andaman	Nicobars
Jharkhand	2.61%	Livestock	Crop Field	Coal Mine	Hazaribagh	Ranchi	Dhanbad
Punjab	2.59%	Crop Field	Livestock	CRB	Ludhiana	Bathinda	Sangrur
Haryana	1.89%	Livestock	Crop Field	Oil & Gas	Karnal	Sirsa	Panipat
Kerala	1.35%	Wetland	Livestock	MSW	Ernakulam	Alappuzha	Malappuram
Jammu & Kashmir	0.86%	Livestock	Termite	Forest Fire	Jammu	Rajouri	Reasi

Uttarakhand	0.65%	Livestock	Crop Field	CRB	Udham Singh Nagar	Hardwar	Garhwal
Goa	0.53%	Oil & Gas	Wetland	Livestock	North Goa	South Goa	
Himachal Pradesh	0.49%	Livestock	MSW	Wetland	Kangra	Mandi	Chamba
Mizoram	0.40%	Forest Fire	Livestock	MSW	Lunglei	Aizawl	Mamit
Meghalaya	0.35%	Forest Fire	Livestock	MSW	West Khasi Hills	Ri Bhoi	West Garo Hills
Manipur	0.34%	Forest Fire	Livestock	Crop Field	Tamenglong	Churachan dpur	Senapati
Delhi	0.34%	Waste Water	MSW	Cooking Activities	North West	South West	West
Arunachal Pradesh	0.29%	Forest Fire	Livestock	Termites	Lohit	West Siang	Changlang
Nagaland	0.25%	Forest Fire	Livestock	CRB	Mon	Wokha	Peren
Tripura	0.17%	Livestock	Forest Fire	MSW	Dhalai	North Tripura	Gomati
Puducherry	0.05%	Wetland	Oil & Gas	Crop Field	Karaikal	Puducherr y	Yanam
Sikkim	0.04%	Livestock	MSW	Cooking Activities	East District	North District	West District
Chandigarh	0.02%	Waste Water	MSW	Livestock			
Dadra & Nagar Haveli	0.01%	Wetland	Livestock	Crop Field			
Daman & Diu	0.01%	Wetland	MSW	Livestock			
Lakshadweep	0.00%	Wetland	Livestock	MSW			

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