Earth System
Science
Data

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*Supplement of*

# A gridded ($0.1° \times 0.1°$) methane emission dataset for India for 2023 to redefine global climate studies

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1    **Section S1**

2    **Emission estimation:**

3    The total methane emission budget is the summation of sectoral methane emission which is
4    calculated by using equation S1.

5    $$E_{CH4} = \sum_{Sources} AD \times EF \qquad \text{Eq (S1)}$$

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

8    **Livestock: -**

9    The $CH_4$ emissions from livestock are broadly classified into two categories, i.e., enteric
10   fermentation and manure management. The emission from enteric fermentation comes from the
11   digestive process of the ruminants, which varies with age, gender, species, temperature, living
12   conditions, and grazing pattern.  This study incorporates 10 livestock species, which are further
13   discretized according to age and productivity. The population under each category is taken from the
14   20th livestock Census-2019, a national-level livestock population survey, which is extrapolated for
15   the year 2023, accounting for 548.7 million livestock and 2.7 billion poultry [DAHD, 2019]. India,
16   home to more than half of the world's livestock, possesses the largest bovine population globally.
17   The accumulation of livestock population is predominantly found in Northern India, Indo-Gangetic
18   Plain (IGP), and Decan Plateau Regions (DPR). To take accountability for the $CH_4$ emission, a
19   comprehensive species-wise analysis was carried out at the district-level and further defined at the
20   village-level. The emission for individual categories is calculated as per equation S2.

21   $$E_{LS}(\text{Tg/yr}) = \sum_{Species} \frac{P_{LS}}{10^9} \times EF_{LS} \qquad \text{Eq (S2)}$$

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

26    **Agricultural Practices: -**

27    Vegetative agricultural practices, particularly rice and sugarcane cropping, are one of the leading

28    sources of $CH_4$ emissions globally [Saunois et al., 2020]. India, which bears a suitable agro-climatic

29    zone, has emerged as the second-largest producer of rice and sugarcane in the world [USDA, 2024].

30    These crops are cultured in the flooded water regime, which lead to $CH_4$ emissions due to anaerobic

31    disintegration of organic materials in the waterlogged soil. This $CH_4$ diffuses into the atmosphere

32    through plants. The emission is largely influenced by various other factors like water availability,

33    cropping pattern, weather, soil structure, fertilizer usage, etc [Saunois et al., 2020]. The geographic

34    distribution of extensive cropping patterns increases the emission of $CH_4$ in the rice belt (i.e., IGP,

35    Northeastern states, Eastern coastal states). The crop fields in these areas are classified as rainfed,

36    irrigated, deepwater, and upland areas. The total $CH_4$ budget is the resultant of emissions from all

37    the water regimes (WR) for rice and sugarcane crops that can be formulated as:

38
$$E_C \text{ (Tg/yr)} = \sum_{WR} \frac{A_C}{10^9} \times PC_{WR} \times EF_{WR} \qquad \text{Eq (S3)}$$

39    Where $E_C$ is the emission from the crop field (i.e., rice or sugarcane), $A_C$ is total area of cropping, $PC_{WR}$

40    is percentage (%) of a particular water regime and $EF_{WR}$ is the $CH_4$ emission factor for that particular

41    water regime.

42    **Waste management: -**

43    **Solid Waste Burning: -**

44    The waste management sector ranks as the third largest contributor to global indirect GHGs

45    emissions [USEPA, 2012]. India is a global production hub and emerging economy, where waste

46    generation and its management have emerged as the biggest sustainable burdens recently

47    [Mangaraj et al., 2022a, 2022b, 2024a, 2024b]. This study quantifies the emission of $CH_4$ from waste

48    sources that include municipal solid waste (MSW) landfilling and open burning, along with

49    residential and industrial wastewater treatment, by adopting the IPCC tier II/III bottom-up approach.

50    Methane emissions from waste management primarily result from the anaerobic decomposition of

51    organic matter in both solid waste and wastewater. These emissions are closely tied to the

52    population density and living standards of the region, with higher emissions typically observed in

53    cities with populations exceeding 0.1 million. The current estimation is based on the per capita solid

54    waste generation in different living conditions like cities, rural areas, etc., which is fragmented

55    according to Tier I, II and III cities and rural India. As per CPCB's annual report on Solid waste

56    Management (2021), 30% of waste is burned openly, which emits $CH_4$ into the atmosphere [CPCB,

57    2021]. We calculated the same using equation S4.

58
$$E_{MSWB}(\text{Tg/yr}) = \left\{\frac{\sum P_{i,j,k} \times MSW_{i,j,k}}{10^{12}}\right\} \times PC_B \times EF_B \qquad Eq(S4)$$

59    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

60    population in that region, MSW is solid waste generation per capita, $PC_B$ is the percentage of waste

61    burnt, $EF_B$ is $CH_4$ emission factor (g/kg) for waste burning.

62    **Solid Waste Landfilling: -**

63    In landfills, $CH_4$ is emitted due to the anaerobic disintegration of decomposed waste. Open dumping

64    of solid wastes is the emerging concern across the Indian subcontinent. Nearly one-third of the total

65    MSW generation is openly dumped as per the CPCB report (2021). Besides this, landfilling and

66    composting account for ~20% and 7.5% respectively, which is responsible for $CH_4$ emissions

67    through methanogenesis [CPCB, 2021]. The $CH_4$ emission from landfilling is calculated considering

68    all three waste management practices in this study, which can be formulated as equation S5.

69
$$E_{MSWL}(\text{Tg/yr}) = \left\{\frac{\sum P_{i,j,k} \times MSW_{i,j,k}}{10^{12}}\right\} \times \sum_{O,L,C} PC \times MCF \times DOC \times DOC_F \times F \times \left(\frac{16}{12} - R\right) \times (1 - OX) \qquad Eq(S5)$$

70    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

71    the population in that region, MSW is solid waste generation per capita, PC is the percentage of

72    waste managed under various categories, O is open dumping, L is landfilling and C is composting,

73    MCF is the Methane correction factor, considered 0.4,

74    DOC is the Degradable organic carbon, considered 0.114,

75    $DOC_F$ is the Dissimilated fill gas, considered 0.77,

76    F is the Fraction of $CH_4$ gas, considered 0.5,

77    R is the recovered methane gas, considered 0,

78    OX is the oxidation factor, considered 0.

79    **Wastewater Management: -**

80    Similarly, $CH_4$ is emitted from wastewater in landfilling sites due to the anaerobic decomposition of
81    organic matter. So, the governing factor in potential $CH_4$ generation is the amount of degradable
82    organic matter present in the wastewater. The emission of $CH_4$ from wastewater is divided into two
83    categories: residential and industrial wastewater, calculated by equation S6.

84
$$E_{WW}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{R,I} WW_T \times BOD \times MCF \times B_O \times \frac{365}{10^9} \qquad \text{Eq(S6)}$$

85    Where $E_{WW}$ is the emission from wastewater, R and I denote residential and industrial wastewater,
86    $WW_T$ is the wastewater treated at the treatment plant (l/day), BOD is the total organic waste load
87    (mg/l), MCF is the Methane correction factor, considered 0.5, $B_O$ is the maximum methane-
88    producing capacity of raw sewage (kg $CH_4$/ kg BOD), considered 0.6.

89    **Forest Fires: -**

90    Forest fire events are disrupting the terrestrial ecosystem globally, making it a significant contributor
91    to air pollution and climate change. With a total forest area of ~80.9 million ha, India ranks 10th in
92    the world and ranks third in net gain in forest cover in the last decade [MoF, 2023]. However,
93    ~212249 forest fire incidents were observed in 2022, affecting ~3.85 million ha of forest area in the
94    country [MoEFCC, 2023]. $CH_4$ is emitted from biomass burning due to incomplete combustion
95    conditions, and the rate of emission is modulated by the type of biomass and the biomass load.
96    Thus, the amount of $CH_4$ emitted in different forest fire events is calculated according to the forest
97    type using equation S7.

98
$$E_{FF}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{FT} \frac{A_{FF}}{10^{12}} \times PC \times BL \times FB \times EF \qquad \text{Eq(S7)}$$

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

102   **Crop Residue Burning: -**

103   Crop residue burning is a pressing challenge in the Northern, Northeastern and Indo-Gangetic states
104   of India [Sahu et al., 2021]. To prepare the crop field for next cropping, farmers deliberately burn the

105    residues of the last crop. This traditional slash-and-burn approach to crop residues worsens the

106    surrounding air quality by emitting $CH_4$. The amount of $CH_4$ emissions from the crop residue burning

107    depends on the type of crop and the amount of dry matter present in the residue. We have taken a

108    number of major crops, including rice, wheat, cotton, sugarcane, pulses, etc., for the estimation of

109    $CH_4$ emissions, which can be formulated as equation S8.

110    $$E_{CRB}(\text{Tg/yr}) = \sum_{CT} \frac{P}{10^{12}} \times RPR \times DMF \times FB \times EF \qquad \text{Eq(S8)}$$

111    Where $E_{CRB}$ is the emission from crop residue burning, CT is the crop type, P is the production of that

112    crop, RPR is the residue to production ratio of that crop, DMF is the dry matter fraction in the

113    residues, FB is the fraction of residue burnt, and EF is the emission factor of residue burning for each

114    crop type.

115    **Cooking Activity: -**

116        India is home to 1.4 billion people, and they use solid biofuel extensively in cooking activities.

117    The inaccessibility to cleaner fuel makes this sector a significant contributor to air pollution in the

118    country. Usage of wood, coal, crop residues, and cow dung cake, is still predominantly used as

119    cooking fuel in the lower-income categories. With the enactment of the Pradhan Mantri Ujjwala

120    Scheme, beneficiaries are shifting toward LPG consumption more rapidly. The percentage share of

121    cooking fuel characteristics in different household types is taken from the 78th NSS Report 2020-21

122    [MoSPI, 2023]. Similarly, commercial cooking activities like restaurants, hotels, and street vendors

123    are also taken into account in the emission estimation. Their per-day fuel type and consumption data

124    were collected from previously published city-specific studies [Mangaraj et al., 2022a, 2022b,

125    2024a, 2024b, Štimac et al., 2023, Majumdar, 2013]. The emissions from cooking activities are the

126    summation of emissions from both the residential and commercial sources. It is calculated as per

127    equation S9.

128    $$E_{HH}(\text{Tg/yr}) = \sum_{R,S,U} \sum_{C,W,L} T_{HH} \times PC_{HH} \times CF \times EF \times \frac{12}{10^{12}} \qquad \text{Eq(S9)}$$

129    Where $E_{Cook}$ is the emission from cooking activities, R, S, and U are for rural, slum and urban region

130    emission, C,W,L are for fuel type like coal, wood, and LPG, etc., $T_{HH}$ is the total households under

131 that categories, $PC_{HH}$ is the percentage of households using a particular fuel for cooking, CF is the

132 monthly consumption of fuel, EF is the emission factor of the that particular fuel.

**Transportation: -**

134      Methane emissions from the transportation sector are minimal but occur due to the

135 incomplete combustion of various fossil fuels. In recent years, the number of vehicles in India has

136 increased significantly, reaching ~326 million in 2023 [MoRTH, 2023]. This study takes into account

137 an array of vehicle types, including two-wheelers, three-wheelers, personal and commercial cars,

138 buses, and heavy and light-duty vehicles, as well as other miscellaneous vehicles. Additionally, it

139 considers different fuel types used by these vehicles, such as gasoline, compressed natural gas

140 (CNG), petrol, and diesel. The total emissions of $CH_4$ from the transport sector are estimated using

141 equation S10.

$$E_{TRN}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{VT}\sum_{AGE} N \times PC_{OR} \times VKT \times EF \times \frac{365}{10^{12}} \qquad \text{Eq(S10)}$$

143 Where $E_{TRN}$ is the emission from transport sector, VT is the vehicle types, AGE is the vehicle age

144 categories (i.e., 5, 10, and 15 years), N is the number of registered vehicles, $PC_{OR}$ is the percentage

145 of vehicles plying on road, VKT is the distance travel by the vehicle in kilometer in a day, EF is the

146 emission factor of the fuel used.

**Coal Mining: -**

148      A significant portion of anthropogenic methane is emitted during mining operations and

149 predominantly originates from ventilation shafts, where substantial volumes of air are introduced

150 into the mines to maintain the $CH_4$ mixing ratio below 0.5%, thereby preventing accidental ignition.[2]

151 India, with a coal reserve of ~344 billion tonnes, ranks as the fifth-largest country globally in terms of

152 coal deposits and the second-largest in coal production [MoC, 2020]. The monitoring of all coal

153 mines within India falls under the jurisdiction of the Directorate General of Mine Safety. Mines across

154 various states are categorized broadly by surface and underground coal mines, which are further

155 disaggregated by degrees of gassiness (Degree I, II, and III) rather than by size. The total $CH_4$ emission

156 from coal mining activities can be calculated from equation S11.

$$157 \qquad E_{CM} = \sum_{MT} \frac{P_C}{10^3} \times EF \times CF \qquad\qquad \text{Eq(S11)}$$

158  Where $E_{CM}$ is the emission from coal mining, MT is the mine type, $P_C$ is the Production of coal from

159  each mine (tonne), EF is the methane emission factor ($m^3$/tonne), CF is the conversion factor

160  ($0.67 \times 10^{-6}$ Gg/$m^3$)

**Oil and Gas Production and Refining**

162  Though India has extremely limited oil and natural gas reserves, the refineries do contribute

163  significantly to $CH_4$ emissions from this sector. As natural gases are primarily composed of $CH_4$, it

164  diffuses into the atmosphere during the extraction and refining process. The estimated $CH_4$

165  emissions from this sector can be formulated as equation S12.

$$166 \qquad E_{OIL}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{E,R} \frac{V}{10^{12}} \times EF \qquad\qquad \text{Eq(S12)}$$

167  Where $E_{OIL}$ is the emission from the oil and natural gas sector, E, and R are the extraction, flaring and

168  refining of oil and natural gas, V is the volume of extraction, flaring and refining of oil and natural gas

169  and EF is the $CH_4$ emission factor associated in each process.

**Thermal Power Plants**

171  In India, coal-based power plants satisfy approximately half of the national energy demand. As of

172  2022, the total installed capacity of thermal power plants is approximately 237,268.9 MW [CEA,

173  2023]. This sector consumes around 709.86 million tonnes of coal and 38.76 million tonnes of lignite

174  [ESI, 2023]. The extensive use of coal for energy production renders this sector unsustainable and

175  significantly influences regional air quality. Methane emissions resulting from the combustion of

176  these fuels are quantified based on the fuel consumption data of individual plants as per equation

177  S13.

$$178 \qquad E_{TPP}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{C,L} \frac{F}{10^{12}} \times EF \qquad\qquad \text{Eq(S13)}$$

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

**Brick Kilns**

182   India holds the second position globally in brick production, with an annual average output of
183   approximately 250 billion bricks produced by 144,000 operational brick kilns [Rajarathnam et al.,
184   2014, Eil et al., 2020]. This sector is responsible for the annual consumption of nearly 41 million
185   tonnes of coal and 31 million tonnes of biomass [Tibrewal et al., 2023]. The methane emissions from
186   this sector are determined by using equation 13 based on the consumption of coal and biomass by
187   the brick kilns.

**Crematories**

189   The traditional pyre systems commonly utilize wood for combustion, which may also contribute to
190   $CH_4$ emissions. According to the World Bank (2023), India's current crude death rate (CDR) is 9
191   [World Bank, 2023]. Approximately 80% of the population, or around 1.13 billion Hindus, practice
192   the traditional pyre cremation predominantly [Census, 2011]. It is estimated that there are about
193   10.2 million deaths among the Hindu community, with nearly 10% of these bodies being cremated
194   using electric methods, while the remaining 90% are traditionally burned. The cremation of a single
195   body typically requires around 550 kg of wood [Mangaraj et al., 2022a, 2022b, Sahu et al., 2023,
196   Chakrabarty et al., 2013]. The $CH_4$ emissions from this sector can be calculated by multiplying the
197   number of deaths, the wood consumption per individual, and the corresponding emission rate as
198   per equation S14.

$$E_{CRM}\left(\frac{\text{Tg}}{\text{yr}}\right) = \frac{P_T}{10^{12}} \times PC_H \times MR \times PC_{TB} \times F_W \qquad \text{Eq(S14)}$$

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

**Wetlands**

205    Wetlands are generally defined as ecosystems characterized by waterlogged or saturated soils or

206    peats, where anaerobic conditions promote methane production [Anderson et al., 2010]. This

207    study encompasses all inland freshwater sources, such as ponds, rivers, and lakes, as well as

208    coastal brackish water sources and coastal vegetative ecosystems, including mangroves. In India,

209    4.6% of the land area is covered by natural and artificial wetlands, featuring an extensive coastal

210    length of approximately 7,500 km and around 5,000 $km^2$ of mangrove forests. These regions are

211    predominant in methane emission. The three principal factors influencing methane production in

212    wetlands are the spatial and temporal extent of anoxia (associated with water saturation),

213    temperature, and substrate availability [Wania et al., 2010, Whalen et al., 2005]. Temperature

214    variability and geographical location play a significant role in determining the emission profile. To

215    assess these factors, this study utilized temperature data from the Indian Meteorological

216    Department's                    annual                    gridded                    dataset

217    (https://www.imdpune.gov.in/cmpg/Griddata/Max_1_Bin.html), along with productivity factors

218    sourced from various published scientific literature [Garg et al., 2005]. Taking into account the

219    above factors, $CH_4$ emission can be derived from equation S15.

220
$$E_{WL}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{WT} \frac{A}{10^{12}} \times MF \times TF \times PF \qquad \text{Eq(S15)}$$

221    Where $E_{WL}$ is the emission from the wetland, WT is the wetland types, A is the area of the wetland,

222    MF is the observed methane emission flux, TF is the temperature factor = $e^{0.334(T-23)}/1 + e^{0.334(T-23)}$, where

223    T is the surface temperature, PF is the productivity factor, considered 0.25 for high-altitude

224    wetlands, 0.5 for the rest of India, and 1 for mangroves [Garg et al., 2005].

225    **Termites**

226    Termites, classified under the infraorder Isoptera, predominantly inhabit tropical and subtropical

227    latitudes [Abe et al., 2000]. Methane emissions from termites are produced by symbiotic

228    microorganisms within their digestive systems. The estimation of $CH_4$ emissions from termite nests

229    employs the methodology developed by Sanderson M.G. (1996), which calculates emissions based

230    on termite biomass per unit area of forest and the $CH_4$ flux per unit termite biomass which can be

231    formulated in equation S16.

232
$$E_{TRM}\left(\frac{\text{Tg}}{\text{yr}}\right) = \sum_{FT} A \times TB \times MF \times \frac{24 \times 365}{10^{12}} \qquad \text{Eq(S16)}$$

233 Where $E_{TRM}$ is the emission from termites, FT is the forest type, A is the area of that forest type, TB is

234 the termite biomass per unit forest area, and MF is the $CH_4$ emission flux per unit termite biomass

235 per hour.

236

237 **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<br>https://censusindia.gov.in/census.website/<br>Ministry of Housing and Urban Affairs<br>https://mohua.gov.in/<br>UN World Urbanization Prospects<br>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<br>https://mohua.gov.in/upload/uploadfiles/files/StreetVendorAct2014 | | | |
| **12** | 1.A.3.b | Transport | Tier II | Ministry of Road Transport & Highway<br>https://morth.nic.in/<br>Ministry of Statistics and Programme Implementation<br>https://www.mospi.gov.in/ | | | |
| **13** | 1.A.1 | Thermal Power Plant | Tier II | Ministry of Power<br>https://powermin.gov.in/<br>Central Electricity Authority<br>https://cea.nic.in/?lang=en | | | |
| **14** | 1.B.1 | Crematorium | Tier II | Ministry of Home Affairs<br>https://www.mha.gov.in/en<br>SAFAR- Delhi (2018), Pune (2020) | | | |
| **15** | 1.B.1 | Brick Kiln | Tier II | Central Pollution Control Board<br>https://cpcb.nic.in/<br>Seay et al., (2021)<br>https://doi.org/10.1088/2515-7620/ac0a66<br>Rajarathnam et al., (2014)<br>https://doi.org/10.1016/j.atmosenv.2014.08.075 | | | |
| **16** | | Termite | Tier I | Ministry of Environment, Forest and Climate Change<br>https://moef.gov.in/ | | | |

238

239 **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 | |

| | | | | | |
|---|---|---|---|---|---|
| | 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 | [NATCOM, 2004, 2012, IPCC, 2006, Garg et al., 2011, Samal et al., 2024] |
| | 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 | |
| **Ducks** | | | | 0.01 | 0.01 | [Zhou et al., 2007] |
| **Geese** | | | | 0.02 | 0.02 | |

| | | | | | |
|---|---|---|---|---|---|
| **Turkeys** | | | 0.11 | 0.11 | |

240

**Table S3: Country-specific emission factors 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 | |

| | | Units | Value | Range | Reference |
|---|---|---|---|---|---|
| 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

| | | Units | Value | Reference |
|---|---|---|---|---|
| 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 | |

| | | kg CH$_4$/kg BOD | 0.6 | |
|---|---|---|---|---|
| | Maximum Methane Production Potential (Bo) | | | |

**(d) Oil & Gas**

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

**(e) Coal Mining**

| | | | | |
|---|---|---|---|---|
| Surface Mining | | | 1.18 | |
| Underground Mining | Degree—I | m3/tonne | 2.91 | [Singh et al., 2016] |
| | 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 | | 9.59 | |
|---|---|---|---|
| Wheat | | 3.55 | |
| Maize | | 4.4 | |
| Coarse cereal (Sorghum) | | 4.4 | |
| Jute | g/kg | 4.56 | [Khaiwal et al., 2019, Sahai et al., 2007, Kanabkaew et al., 2010, Li et al., 2022] |
| 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 | | 7.9 | |
| Dung | g/kg | 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 | | 0.15 | [Garg et al., 2011, Pandey et al., 2014, Gurjar et al., 2004] |
| Biomass | g/kg | 6.4 | |

**(j) Termite**

| | | | |
|---|---|---|---|
| Very dense forest | | 6.16 | |
| Moderately dense forest | | 1.77 | |
| Open forest | g/g termite mass/hr | 7 | [Sanderson et al., 1996, European Commission, 2018] |
| Scrub | | 1.7 | |
| Agricultural land | | 3.9 | |

242

243

244    **Table S4: Emission Factor for the Transport Sector**

| Category | Subcategory | | | Reference |
|:---:|:---:|:---:|:---:|:---:|
| | 5yr | 10yr | 15yr | |
| 2W (Gasoline) | 0.0417 | 0.0558 | 0.18 | |
| 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 | [Gurjar et al., 2004] |
| 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 | |

245

246    **Section S2**

247    **Uncertainty Estimation**

248    The evaluation of uncertainty serves as a crucial parameter for EI development, which are

249    foundational in establishing control measures. The initial stage of this analysis entails a

250    thorough examination of the uncertainties inherent in both activity data and emission

251    factors (EFs). Additionally, it is acknowledged that the selected emission factors may not

252    adequately represent the current circumstances. To address this, uncertainty calculations

253    have been conducted using both linear error propagation and the Monte Carlo simulation

254    method, in accordance with IPCC guidelines. The detailed methodologies of uncertainty

255    estimation through the above methods are presented in our previous studies [Mangaraj et

256    al., 2024a, 2024b, Samal et al., 2024, Sahu et al., 2024, Sahoo et al., 2024]. The Linear Error

257     Propagation Method is a first-order analytical technique recommended by the IPCC for

258     estimating uncertainties in emission inventories. It assumes that total emissions are derived

259     from the product of activity data and emission factors, each associated with inherent

260     uncertainty due to data variability or measurement limitations. These uncertainties are

261     combined mathematically through a root-sum-of-squares approach, which assumes

262     independence between variables and linear relationships among them. The resulting value

263     represents the combined relative uncertainty of the emission estimate. However, it does not

264     account for non-linear behaviour and thus may underestimate uncertainty in complex

265     cases. So, IPCC prescribed a Monte Carlo simulation Method to address the non-normal

266     distributions and asymmetry in the dataset. In the Monte Carlo Simulation (MCS) approach,

267     uncertainties associated with source-specific activity data and emission factors are

268     characterized through appropriate probability distribution functions, such as Normal, Log-

269     Normal, Student's t, Triangular, or Uniform distributions, depending on the statistical nature

270     of the input data. The method involves repeatedly drawing random samples from these

271     distributions and computing emission estimates for each iteration. This iterative process,

272     typically performed 100,000 times, produces a probabilistic distribution of emission

273     outcomes. From this distribution, key statistical parameters namely, the mean, standard

274     deviation, and the 95% confidence interval, are computed to quantify the overall uncertainty

275     associated with each emission sector. All the essential statistical computations are

276     performed in the IBM SPSS 24.0 software (https://www.ibm.com/spss).

277     **Section S3**

278     **GIS-based spatial allocation of emissions:**

279     The spatial distribution of emissions is a complex task in terms of analysis and modeling.

280     Geographic Information Systems (GIS) possess the capability to organize spatially

281     heterogeneous data layers. Each emission dataset is aligned with a gridded cell layout to

282     ensure accurate source data aggregation by consolidating control points within each cell.

283     The geographical region of India encompasses 785 districts and is disaggregated into 30,185

284     grid cells, each with a resolution of 0.1° x 0.1° using ESRI ArcGIS 10.6

285 (https://www.esri.com/en-us/home). The gridded emission map is developed through a
286 GIS-based statistical approach, wherein source-specific emission layers (including
287 livestock, wetlands, crop fields, transportation, residential cooking, municipal solid waste,
288 power plants, etc.) are created utilizing spatial information on sector specific activity data
289 or fuel used. The resultant emissions are then organized as thematic layers. This
290 methodology has been extensively employed in emission inventory development [Mangaraj
291 et al., 2024a, 2024b, Sahu et al., 2021, Sahu et al., 2024, Sahoo et al., 2024].

292        As emissions from various sectors are consolidated to form the total emissions
293 within the gridded cells, they are systematically arranged in the form of thematic layers for
294 each sector type, facilitating individual analysis. The preparation of sectoral emission layers
295 necessitates geospatial data, including details about India's road networks, geographic
296 areas, and population.

297 **Livestock:** The livestock population was taken from the 20th livestock census-2019, which
298 provides the district-level livestock population for 10 distinct livestock species. Then the
299 population was upscaled to village level using proxies like rural population and availability
300 of agricultural land. In the absence of population census data for 2023, the village-level
301 population from the 2011 census data has been considered and extrapolated for the base
302 year 2023. We have accessed the agricultural land from the ESRI-land Use land cover (LULC)
303 map of India. The agricultural land was then imported to the ArcGIS software to scale up to
304 the village level. The higher the rural population and agricultural area in a village, the higher
305 the livestock population as villages with larger rural populations and greater agricultural
306 areas generally tend to have higher livestock populations, considering the fact that farming
307 communities largely rely on livestock for agriculture, income, and household needs. Later,
308 the category-wise livestock population is distributed over the village shapefile. The village
309 level species-specific emission is calculated and distributed accordingly with precise
310 political boundary data which accounts nearly 0.63 million spatial emission datasets. The
311 village-level emission file is imported into the GIS environment using ArcGIS tools, and a new
312 0.1˚×0.1˚ gridded map is created based on weighted village-wise livestock contributions

313    within each grid cell, followed by spatial  distribution of  methane emission. Both datasets
314    were then intersected with each other and checked for duplicate entries and multiple
315    overlaps through frequency analysis. Finally, the per-grid emission were obtained and
316    plotted.

317    **Agricultural Field:** In case of major crop like rice and sugarcane, the $CH_4$ emission were
318    calculated on the basis of each crop's cropping area in the districts and the water regime
319    present there. The cropping area and irrigated land data were been retrieved from the Dept.
320    of Agriculture and Farmers Welfare, Govt. of India. District-wise cropping area of rice and
321    sugarcane were extracted from the ESRI-agricultural land shape files in GIS environment
322    individually and allocated to village level based on spatial interaction. This was extrapolated
323    to 0.1˚ x 0.1˚ grids, and run for frequency check and area re-calculation. On the basis of the
324    per-grid cropping area, the emission is redistributed at fine resolution.

325    **Wetlands:** Wetlands consists of Inland wetland, Coastal wetland, and Mangroves. The data
326    are accessed from the Wetlands of India Portal. The wetland maps obtained were
327    georeferenced and digitised using ArcGIS tools, and have been segregated for categories
328    like lake, pond, wetlands and coastal wetlands. Each of the wetlands has been separately
329    layered and processed to generating the gridded map, going through the intersection,
330    frequency and area re-calculations, and the final per-grid area of each wetland type has
331    been prepared. As $CH_4$ emission from wetland is a temperature-dependent phenomenon,
332    we incorporated the average temperature from the National Centre for Medium Range
333    Weather Forecasting (NCMRWF)for further processing and gridded emission calculation
334    and distribution accordingly.

335    **Point sources:** Fossil fuel production and refinery, Thermal power plants, Brick kilns, and
336    Crematorium units are point sources. The data corresponds to the point sources are
337    retrieved from various government reports (Sources mentioned in table S1) and their
338    locations  were collected manually from Google maps. The spatial allocation of emissions
339    was based on points extrapolated into grids and mapped. Each grid cell containing relevant
340    units was assigned the corresponding sectoral emission value calculated using the

341     equation. Grids with greater capacities and a higher diversity of emission sources exhibited

342     higher overall emissions.

343     **Waste management:** Municipal solid waste burning and landfilling were both considered

344     under waste management. Activity information on per-capital and population density were

345     collected from government agency like Central Pollution Control Board (CPCB). Regions

346     with larger populations tend to generate greater amounts of waste. Variations in waste

347     generation patterns are influenced by lifestyle differences, as urban populations generally

348     produce more waste than their rural counterparts. Thus, urban agglomeration having more

349     than 100000 population were masked out which comes out to be more than 1000 cities. The

350     MSW burning and open dumping is distributed as per the gridded population distributions.

351     The major landfilling site locations were loaded in grids and the emissions were assigned to

352     those particular grids. Similarly, emissions from domestic and industrial wastewater

353     treatment plants were assigned to the locations of Sewage treatment plants and Common

354     Effluent Treatment Plants. The emission distribution was based on the wastewater

355     treatment capacity of that particular plant and assigned to the respective grid.

356     **Biomass Burning:** Forest fire and agricultural crop residue burning were considered under

357     this category. NASA-FIIRMS active fire counts (VIIRS) data was used as proxy to spatially

358     allocate emissions. From the ESRI-LULC data, forest area was masked out, and the fire

359     points that overlaid on the forest area were considered as forest fire. The emission is

360     distributed according to the intensity of that fire reported in the fire count data. Likewise,

361     the fire points present in the agricultural area are regarded as the crop residue burning

362     events. The emission distribution also follows the similar procedure. After identification of

363     forest fire and crop residue burning, the data was intersected with the gridded mapper-grid

364     emission was achieved.

365     **Residential & Commercial Cooking:** Cooking activities were distributed on the basis of

366     population residing in rural, urban and slums. Urban slum clusters were identified from each

367     state and the emission is calculated and distributed accordingly. Major slum areas

368     identified manually and from state reports and then georeferenced and digitised in ArcGIS

369    for further processing. The slum locations were then intersected with the gridded map, and

370    after post-processing, the slum population per grid was calculated. The emission is then

371    distributed accordingly. The data for hotel and restaurants are taken from the medium,

372    small and micro enterprises, and the locations are loaded in the gridded map to assign the

373    emission. Street vendors were distributed in the urban agglomeration, i.e., which cities

374    having higher population and higher street vendors are assigned with higher emission

375    polygons. The gridded emissions are distributed on the major and minor road networks

376    running through the cities and people residing in it.

377    **Transport sector:** This is one of the major sectors in which the emission distribution was

378    tedious. The road network of 6.6 million kilometres was accessed from the OpenStreetMap

379    and loaded into ArcGIS interface. National Highways (NH), State Highways (SH), Major

380    Roads, and Minor Roads were segregated with their individual type total road length.

381    Additionally, the vehicle density in the NH and SH were calculated from the vehicles

382    crossing toll plazas. Heavy vehicle mobility is carefully distributed over the NH & SH,

383    complying with the interstate vehicle movement. The emissions from the transport sector

384    were distributed on the basis of the number of registered vehicles present in the states

385    distributed across the road networks present in that state. Since the heavy commercial

386    vehicular activities are usually high in activity areas like Point of interest (POIs) like mining

387    areas, Industries, etc, higher vehicular weightages were given to the POIs for better

388    representation of the emission scenarios complying with the real-life scenarios. NH & SH

389    road networks, major roads, minor roads, residential roads and points of interest were

390    overlaid the grids and emissions were assigned to the grids that intersected, where the grid

391    containing the higher proxy data were assigned with higher emissions.

392    **Termites:** Lastly, the termite sector was distributed on the forest area and the termite

393    biomass present per square meter of forest land. The forest region was mapped from the

394    ESRI-LULC data and then different forest types were segregated according to the species

395    present. The file was intersected with the grids, and the grid containing the forest area was

396    recalculated post-processing. The emissions were then distributed according to the forest

397    area present in that particular grid.

398    **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 | Ahmedabad |
| Maharashtra | 8.65% | Wetland | Livestock | Crop Field | Mumbai Suburban | Pune | Ahmednagar |
| 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 | Angul | 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 | Mahabubnagar |
| 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 | Nicobar |
| 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 | Haridwar | 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 | Churachand pur | 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 | Puducherry | 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 | | | |

399

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