A Gridded (0.1°X0.1°) Methane Emission Dataset for India for 2023 to Redefine Global Climate Studies

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13 **Abstract**

14 Methane (CH_4) is a predominant climate-forcing agent and has become a focal point of

15 global climate discussions, owing to its significant contribution to atmospheric warming.

16 The ambiguity surrounding the relative contributions of various natural and anthropogenic

17 sources, coupled with associated uncertainties, poses significant challenges to assessing

18 methane emissions in developing nations like India. To address these challenges and better

19 understand the methane-emitting sources, this study presents a comprehensive high-

20 resolution gridded (0.1°×0.1°) inventory of CH_4 emission by including 25 distinct

21 anthropogenic and natural sources in India for 2023 by adopting the IPCC bottom-up

22 approach. The estimated CH_4 over India is 37.79 Tg/yr, which will redefine the contribution

23 of various sources. The agriculture sector contributed ~50% followed by wetlands (8.6%),

24 fossil fuel and waste management. This study reports the first-ever comprehensive

25 emissions from natural sources like wetlands and termites. The Indo-Gangetic Plain (IGP)

26 and coastal states show elevated emissions with Uttar Pradesh contributing the highest

27 (10.8%) followed by Gujarat (9.4%), and Maharashtra (8.6%). However, surprisingly cities

28 exhibit lower CH_4 as compared to other semi-urban/rural regions. This developed dataset

29 can be a valuable input to optimize the climate study by filling the data gap, enabling

30 policymakers to formulate various mitigation measures. The emission dataset can be

31 accessed through the Zenodo repository https://doi.org/10.5281/zenodo.14089138 (Sahu S.

32 K., 2024).

33 Keywords: Methane, Greenhouse Gases, Emissions, Anthropogenic and Natural Activities,

34 Climate change

1. Introduction

Methane (CH_4) is the second most abundant and potent greenhouse gas (GHG) in the atmosphere, after Carbon Dioxide (CO_2) (European Commission, 2023). Its ability to trap heat by absorbing outgoing thermal infrared radiation is 28 times more than CO_2 resulting in 16-25% of atmospheric warming to date (Rosentreter et al., 2021). The surface dry-air mole fraction of atmospheric CH_4 has escalated to 1931 ppb, nearly 2.6 times the level recorded in the preindustrial era of 1750 (NOAA, 2024). The significant rise in CH_4 concentrations necessitates urgent mitigation of methane emissions, given its potential to induce near-term climatic changes and its involvement in the formation of tropospheric ozone.

The global CH_4 emissions in 2017 were estimated through the bottom-up approach amounted to be ~747 (602–896) Tg/yr, primarily contributed by anthropogenic sources (Saunois et al., 2020). China is responsible for the highest emissions with more than 20% of the global anthropogenic CH_4, followed by South Asia (13%), Southeast Asia (8%), and the United States of America (USA) (7%) (Saunois et al., 2020). The anthropogenic emissions are attributed to various sources like livestock, agriculture, solid waste, wastewater management, fossil fuel production, biomass burning, etc. Given the extensive domestic and agricultural practices such as livestock and vegetative culture, South Asian regions are a global hotspot of CH_4 emissions (Saunois et al., 2020). Given the diversity of methane sources across the world, the real challenge lies in identifying the country-specific prevailing and predominant sources that may have a disproportionate contribution to the national total emissions. Understanding regional sources in developing nations like India is paramount, where the spatial diversity of sources is much more complex, to identify and quantify methane emissions comprehensively. As per India's third Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC), Indian agriculture sectors contributed nearly 75% of national total methane emissions in 2016 (excluding Land Use, Land Use Change, and Forestry) (MoEFCC, 2021). Owing to this report, the Government of India (GoI) has implemented numerous policies like the National Livestock Mission, Gobar-Dhan Scheme, National Biogas and Organic Manure Programme,

63   National Mission for Sustainable Agriculture, National Innovations in Climate Resilient

64   Agriculture, and Swachh Bharat Mission under Nationally Determined Contribution (NDC)

65   to curtail CH_4 like GHGs. However, India has not signed the 'Global Methane Pledge'

66   proposed by the European Union and the United States of America to target a 30% reduction

67   in global methane emissions from 2020 levels by 2030. Since, India is one of the largest

68   producers and exporters of agricultural products, particularly from paddy cultivation and

69   livestock farming, addressing food security both domestically and globally is crucial.

70   Consequently, the CH_4 from these sources are viewed as survival emissions rather than

71   luxury emissions (MoEFCC, 2023). So, to account for the efficacy of these policy

72   interventions, we need to have comprehensive updated sector-specific methane emission

73   data and the emission inventory will help us keep track of sectoral emissions and our

74   performance compared to other nations in curbing methane pollution.

75   National multi-sectoral CH_4 emissions were last reported by Garg et al. (2011) for the

76   base year 2008 at the district level (Garg et al., 2011). Although some global inventories have

77   reported CH_4 emissions from India in recent years, they primarily relied on Tier I top-down

78   approach, resulting in inconsistent estimations for several sectors (EDGAR, 2023, Saunois

79   et al., 2016). Given the lack of systematic reporting of sector-specific high-resolution activity

80   data, there is a huge challenge in filling the data gaps that estimate comprehensive sectoral

81   CH_4 emissions in India. Parasher et al. (1996) reported 4 Tg/yr of CH_4 from paddy fields for

82   the first time in 1991. Since then, various studies focusing on specific sectors have been

83   conducted, with livestock, solid waste management, and biomass burning being the most

84   extensively examined sectors concerning CH_4 emission. The CH_4 from the livestock sector

85   have ranged between 7.26 Tg/yr and 15.5 Tg/yr from 1990 to 2022 (EDGAR, 2023, Garg et al.,

86   2001). Notably, there have been only four national multi-sectoral emission inventories

87   during this period, all of which were conducted by Garg et al. (2001, 2006, 2011), where the

88   estimated methane ranges from 17.05 Tg/yr to 20.57 Tg/yr for 1990 and 2008. Apart from

89   livestock and paddy, the waste management sector, encompassing solid waste burning and

90   landfilling, and both domestic and industrial wastewater sectors, is also responsible for a

91   significant share of CH_4. Similarly, activities based on biomass and fossil fuels contribute

92   substantially to national CH$_4$ emissions. However, the lack of updated sector-specific

93   activity data and the coarse spatial distribution of emissions render these estimates

94   incompatible, and huge data gaps lead to large uncertainties in climate studies.

95   Furthermore, it has been observed that many natural and unmonitored sources were

96   excluded from earlier estimates, adding to the uncertainty in identifying regional hotspots.

97   The temporal and spatial diversity of sources outlines the necessity of an updated emission

98   inventory (Sahu et al., 2023, Mangaraj et al., 2022a, 2022b, 2024a, 2024b, Janardan et al., 2024).

99   This study provides a comprehensive development and spatial analysis of sectoral methane

100 (CH$_4$) hotspots across India at a fine resolution of 0.1° × 0.1° by incorporating 25 natural and

101 anthropogenic sources for the year 2023. This study also offers strategic targets for further

102 climate research. The newly developed methane emission database will be invaluable, not

103 only for advancing regional climate research by filling the data gap in the country but also as

104 an essential tool for policymakers in formulating mitigation strategies.

105 **2. Methodology**

106 The present attempt is intended to quantify the recent methane emission budget for India in

107 2023. The study targets 25 natural and anthropogenic sources, including livestock, rice crop

108 fields, wetlands, oil & gas, solid waste, wastewater, and biomass burning, termite,

109 transportation etc., which are the significant emission sectors in the country. The source-

110 specific emissions are estimated in accordance with the IPCC tier II/III country-specific

111 technological emission factors-based bottom-up approach methodology presented in the

112 supplementary file (Sahu et al., 2023a, 2023b, 2021, 2024, Mangaraj et al., 2022a, 2022b,

113 2024a, 2024b, Sahoo et al., 2024, Samal et al., 2024). The importance of the bottom-up

114 approach lies in the compilation of high-resolution activity data (AD) and regional emission

115 factors (EF). The AD entails gathering comprehensive information at each source level, such

116 as species-wise population data of livestock, water regime-wise crop area and cropping

117 pattern for rice and sugarcane cropping, high-resolution spatial information of each source

118 for thermal power plants (TPP), wastewater treatment facilities, type of wetland area for

119 wetlands, vehicular type, volume of traffic and driving pattern, technology used, age of

120   vehicles, fuel use for transportation, waste and wastewater generation waste management,

121   temperature data for wetland, etc. Similarly, country-specific EF is a pivotal component of

122   developing emission inventory as the sensitivity of the EF decides the uncertainty in the

123   estimation and leads to inappropriate spatial patterns of gridded emission. This study

124   ratified the country-specific proxy-level technological EFs for estimation. The details of AD

125   and EF are presented in supplementary Tables S1, S2, S3, and S4 respectively. The bottom-

126   up framework relies on an emission factor-based formulation, in which emissions from each

127   source category are estimated as a function of activity data, technology-specific emission

128   factors, fuel use, and emission control efficiencies. The sectoral total emissions will then be

129   estimated using established formulations, including sector–specific fuel-wise technology–

130   based equations as per equation (1). The emission from the road transport sector

131   specifically has been calculated as per the following equation: -

132    $$E = \sum_a \sum_b F_{a,b} \left[\sum_c Ef_{a,b,c} A_{a,b,c} \right] \tag{1}$$

133   where a, b, c = sector, fuel type, technology; E= Total amount of Emission; F = sector-wise

134   fuel amount; Ef = Country specific technology emission factors; A = amount of fuel

135   associated with particular technology where $\sum A = 1$ for each kind of fuel and sector.

136   The detailed methodology, uncertainty estimation, and spatial allocation of emission are

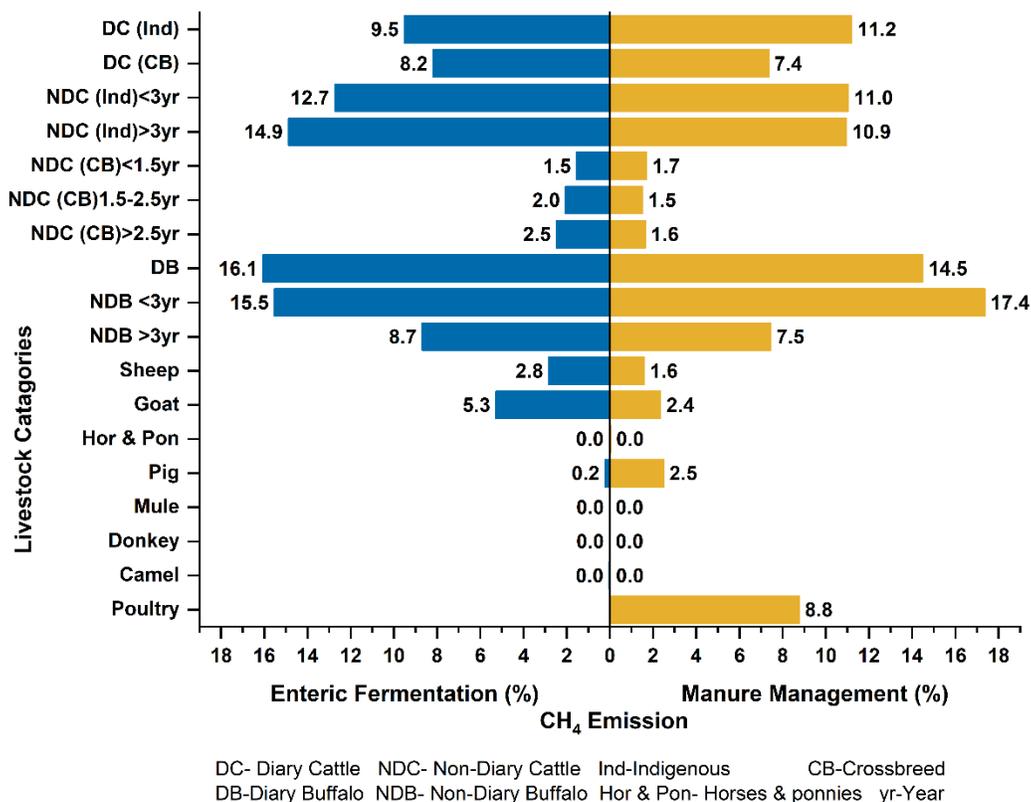137   presented in the supplementary file.

3. Results and discussion

3.1 Sectoral contribution to total CH$_4$ emission

140   The total methane emissions, estimated from 25 types of sources (natural and

141   anthropogenic) in India, is ~37.79 Tg/yr in 2023. The agricultural sector, encompassing both

142   livestock and crop fields, emerged as the predominant contributor, accounting for nearly

143   half (~49%) of the nation's methane emissions. Specifically, livestock enteric fermentation

144   alone is responsible for approximately one-third of agricultural sector emissions, while rice

145   crop fields contributed about 13%. Wetlands constituted the next significant source,

146   contributing more than one-fifth (8.6 Tg/yr) of the national total. This is followed by

147 emissions from fossil fuel-based activities, which accounted for approximately 9% (3.35

148 Tg/yr), waste management (~8%), biomass burning (~5%), cooking activities (~4%), and

149 other miscellaneous sources comprising about ~2% of the total emissions, as illustrated in

150 Figure 1 (a).

151 In the case of livestock, cattle are the major contributors, emitting 6.03 Tg/yr (~51%)

152 of methane due to enteric fermentation. Notably, indigenous cattle are identified as the

153 largest contributors within this category, responsible for ~37% of the emissions, followed by

154 crossbred cattle (~14%). It is observed that non-dairy cattle contributed more significantly

155 to methane (~33%) than dairy cattle (~18%). Buffaloes also contributed a substantial ~40%

156 to the emissions, with non-dairy buffaloes being the primary emitters (~24%), followed by

157 goats (~5%), sheep (~3%), and other livestock species as shown in Figure 1 (b). Moreover, a

158 similar trend is observed in manure management, where cattle are the leading contributors,

159 responsible for ~45% of methane emissions, followed by buffaloes (~39%), poultry (~8%),

160 pigs (~2.5%), goats (~2%), and other species.

161

162

(b)

Fig 1: (a) Sectoral Contribution of CH$_4$ emission (% total), (b) Livestock (% of sector) in 2023

163

164

165

Wetlands have emerged as the second largest source of CH$_4$ emissions in India, where the inland wetlands contribute the highest (~17%) followed by rice fields (~13%). The present attempt examines the comprehensive coastal CH$_4$ budget, revealing that the marine wetlands in coastal areas emit roughly 1.85 Tg/yr. Additionally, the sensitive mangrove ecosystems release 0.84 Tg/yr into the atmosphere. The emission analysis also included data on rice and sugarcane cropping areas, as well as irrigation statistics, retrieved from the Ministry of Agriculture and Farmers' Welfare. The findings indicate that flooded agricultural lands contribute more significantly to methane emissions compared to single-irrigation or drought-prone regions, with rice fields alone responsible for 5.65 Tg/yr of CH$_4$. In addition to wetlands and agricultural lands, MSW landfills are identified as a major source of methane

176 emissions, releasing approximately 2 Tg/yr. This is followed by cooking activities (~1.4 Tg/yr)

177 where residential cooking in both rural and urban localities, slum areas, as well as

178 commercial cooking activities do contribute a good fraction.

179   Further, methane emissions from coal mining and oil and gas extraction processes

180 collectively amount to 1.74 Tg/yr. Additionally, crude oil refining processes contribute

181 another 1 Tg/yr of CH_4. The transport and TPP sector, which rely on these fossil fuels, emit

182 an extra 0.62 Tg/yr. Smaller, but noteworthy, contributions come from fugitive sources like

183 brick kilns and crematories, emitting 0.23 Tg/yr. Lastly, natural methane emissions from

184 termites were also accounted for, contributing approximately 1.5% to the total CH_4 in 2023.

185 **3.2 Spatial variability in CH_4**

186 The spatially resolved estimated CH_4 emissions are crucial in identifying precise dominating

187 sources over particular regions. The resolution of the inventory is a significant parameter, as

188 it allows for the precise identification of hotspots and associated dominating sectors

189 contributing to high emissions. As illustrated in Figure 2(a), CH_4 from livestock are

190 particularly predominant in Western India, the Indo-Gangetic Plain, and the Deccan

191 Plateau. Specifically, the province of Uttar Pradesh contributed the most (~16%) to CH_4

192 emissions from the livestock sector as it outnumbered the other states in cattle and buffalo

193 population. It is then followed by Rajasthan (~10%), Madhya Pradesh (~9%), Bihar (~7%) and

194 Gujarat (~7%). It is very interesting to note that the top 160 districts (out of 785 districts) are

195 responsible for nearly half of the livestock CH_4 emissions with Banas Kantha district in

196 Gujarat being the largest emitter with ~99 Gg/yr.

197   Natural sources like wetlands, especially inland water bodies that constitute rivers,

198 lakes, and ponds are the second largest sources of CH_4 emissions and are well scattered

199 across the country. Figure 2(b) reveals that Eastern India is more susceptible to such

200 emissions induced by inland water bodies compared to Western India, largely due to the

201 eastward flow of most major river systems towards the Bay of Bengal. The Ganges,

202 Brahmaputra, Mahanadi, and Godavari river basins, which span the Eastern, Northeastern,

203   Deccan, and Southern peninsular regions, are identified as significant sources of wetland-

204   based CH_4 emissions. As some of the notable rivers originated from the Western Ghats and

205   flowed east, the Southern peninsula and the Deccan plateau region became a web of CH_4

206   emission, as presented in Figure 2(b). However, Gujarat comes out as the highest with 1205

207   Gg/yr (~18%) emitting state from inland water bodies for the Rann of Kachchh and the

208   presence of significant water bodies like Narmada, Tapti and Sabarmati rivers and several

209   lakes and ponds. In addition to it, this study also encompasses emissions from coastal and

210   mangrove forest emissions. Although the Andaman and Nicobar Islands have the largest

211   coastline in India, Gujarat leads in CH_4 emissions from coastal water bodies, contributing

212   approximately 506 Gg/yr (27%), primarily due to the presence of numerous coastal creeks.

213   Further, West Bengal is the highest emitter of CH_4 from the mangrove ecosystem with 65.1

214   Gg/yr (52%) due to the Sundarbans delta region. Hence, overall, Gujarat emerges as the

215   highest emitting state from wetlands, accounting for approximately 20%, followed by the

216   Andaman and Nicobar Islands (12%), Andhra Pradesh (12%), Maharashtra (12%), and

217   Odisha (10%), It is noteworthy that the top 25 districts contribute to more than half of the

218   total CH_4 from wetlands, with the Kachchh district of Gujarat being the largest emitter from

219   the wetland sector. This is followed by North and Middle Andaman (Andaman and Nicobar

220   Islands), South 24 Parganas (West Bengal), South Andaman (Andaman and Nicobar
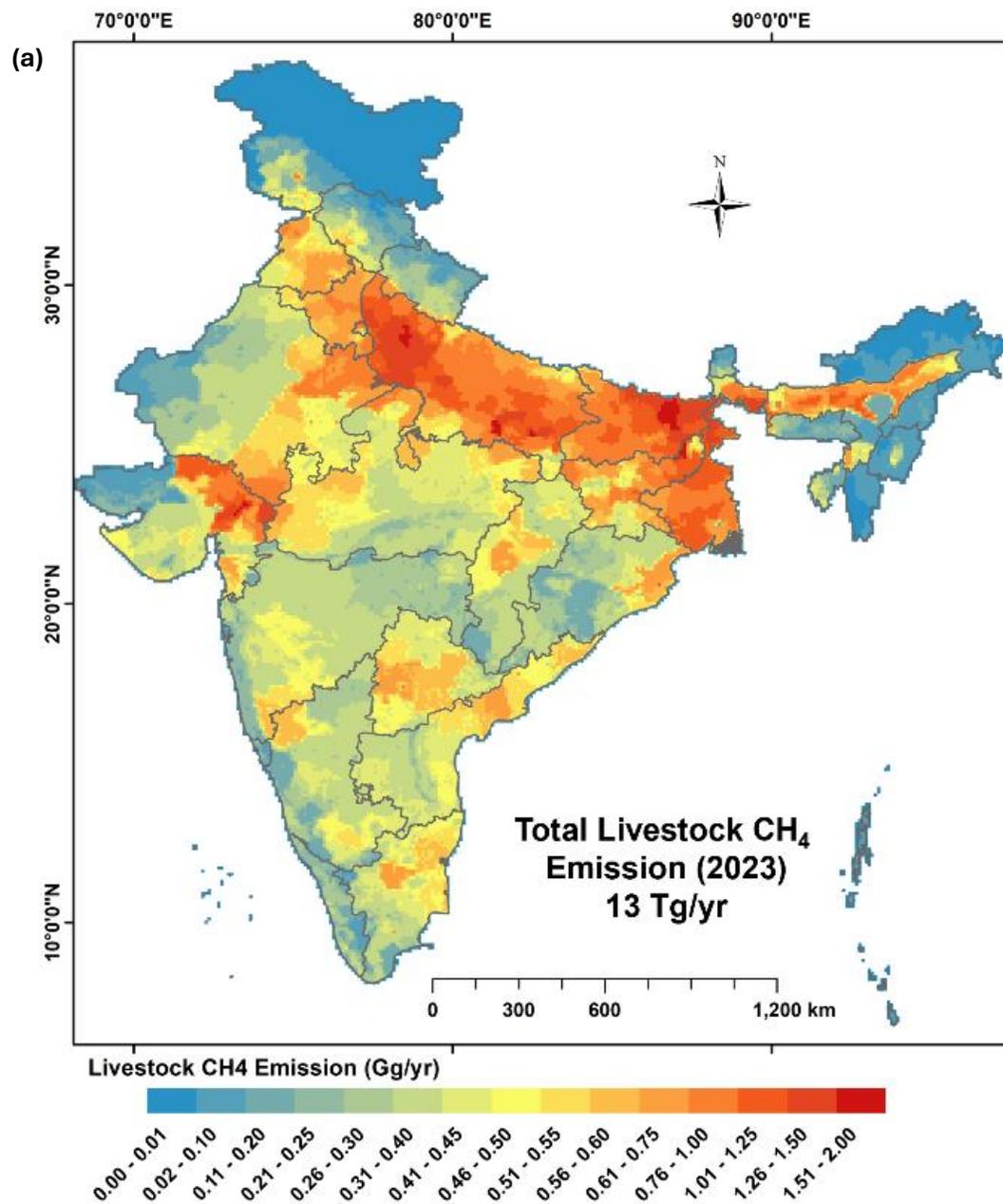
221   Islands), and Nellore (Andhra Pradesh).

222   The spatial distribution of CH_4 from cropland exhibits a pattern closely aligned with

223   that of inland wetlands, particularly in regions where intensive cropping practices are

224   observed near freshwater bodies and experiencing monsoons. Indo-Gangetic basin,

225   Brahmaputra basin, East Coastal, and the Deccan plateau states are the major rice and

226   sugarcane-producing states, as shown in Figure 2(c). Telangana, Uttar Pradesh, and West

227   Bengal are the largest rice-producing states while Uttar Pradesh, Maharashtra, and

228   Karnataka lead in sugarcane production (MoA & FW, 2024). Consequently, Uttar Pradesh

229   emerges as the highest contributor to CH_4 from crop fields, accounting for approximately

230   1022 Gg/yr (18%) of the total, followed by West Bengal 663 Gg/yr (12%), Chhattisgarh 435

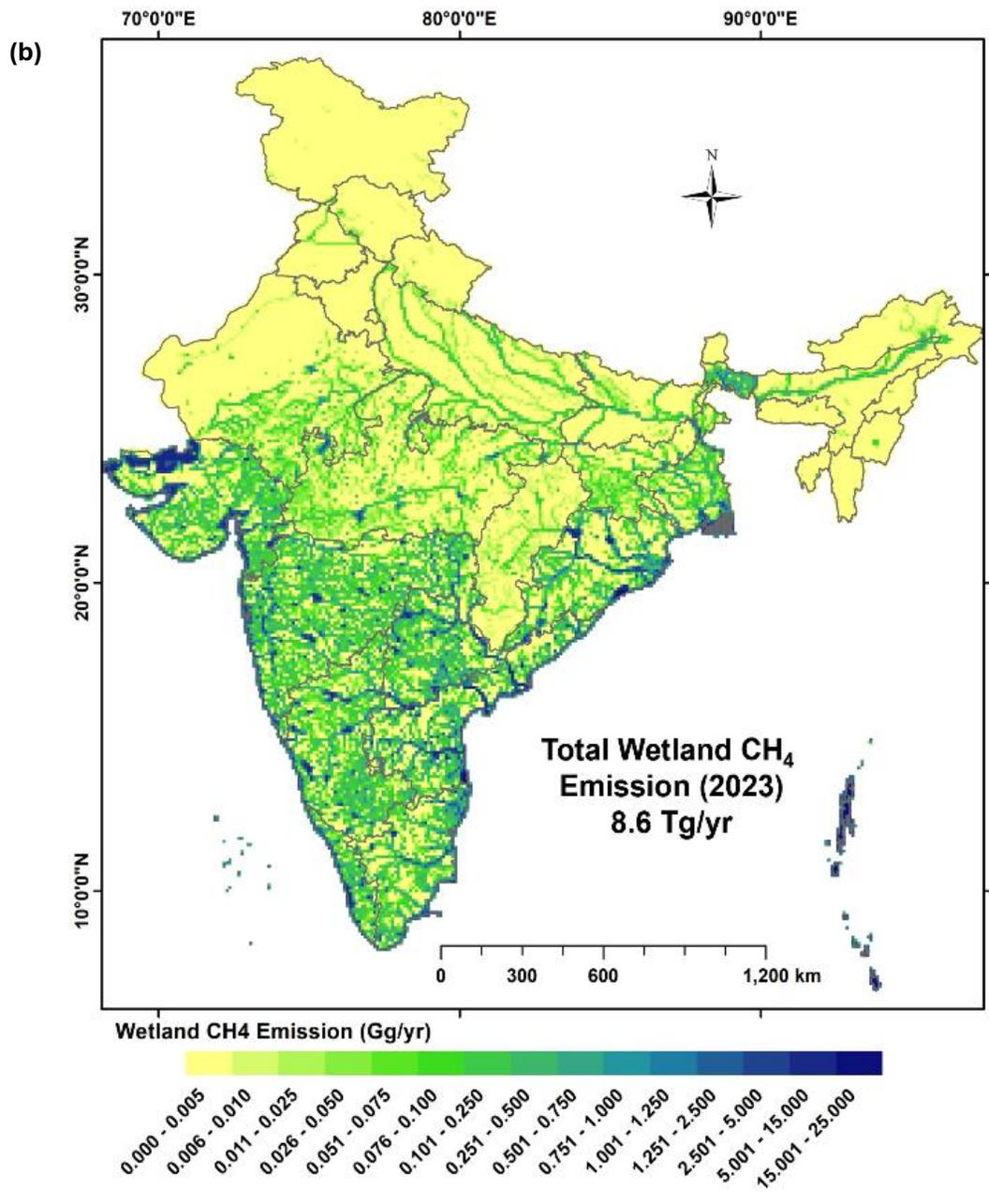231   Gg/yr (8%), Bihar 418 Gg/yr (7%) and Telangana 409 Gg/yr (7%). Notably, over 50% of total

emissions from crop fields originate from the top 90 districts out of which Nalgonda (Telangana), Paschim Medinipur (West Bengal) and Karimnagar (Telangana) are the leading emitters.
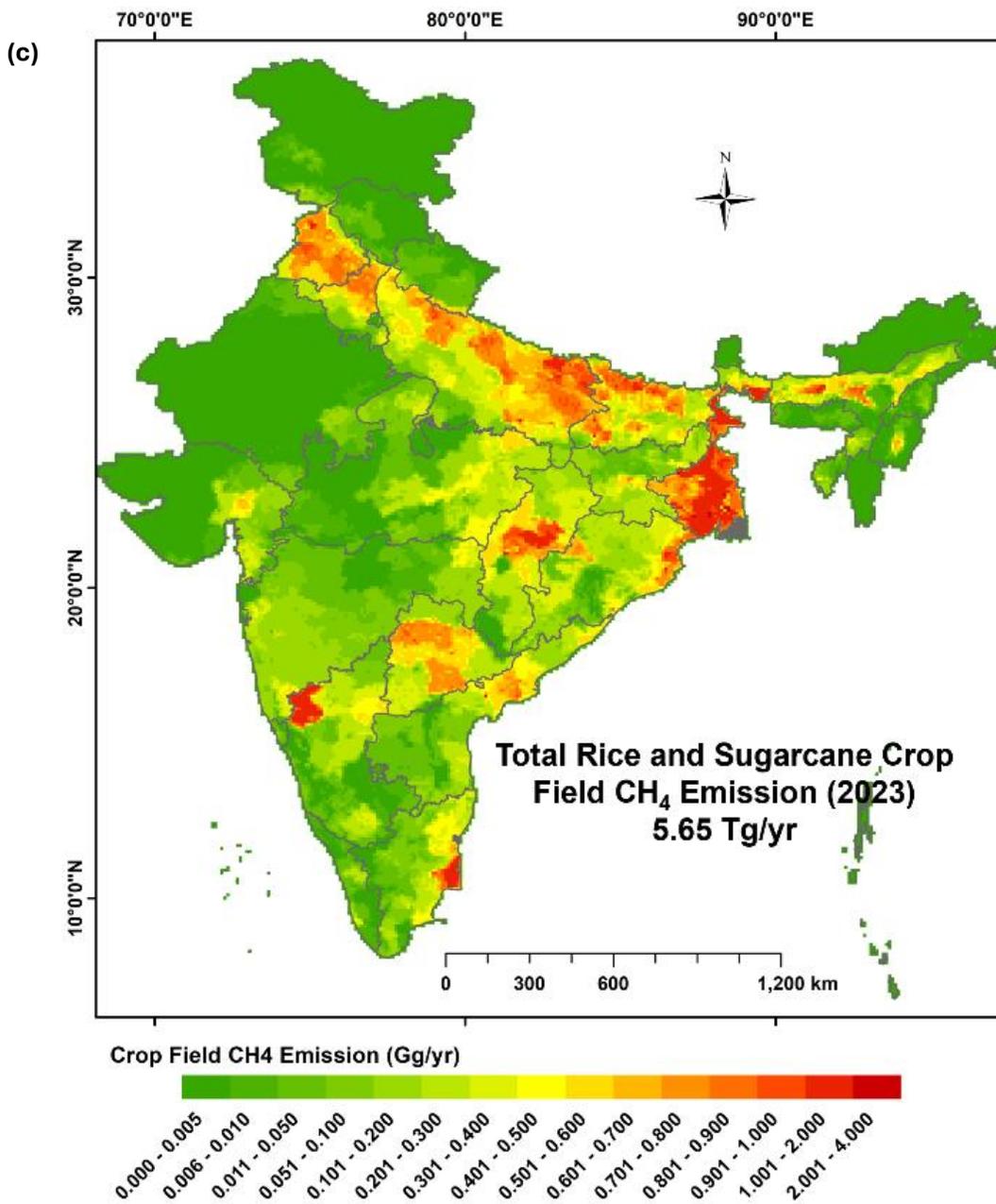
Waste management poses a significant challenge in developing India, where the burden of waste and its associated pollution has adversely affected urban living conditions. It is evident from Figure 2(d) that the Indo-Gangetic Basin states are more susceptible to high emissions than rest India. In solid waste management like burning and landfilling, Uttar Pradesh contributes ~ 303 Gg/yr (13%), followed by Maharashtra ~ 229 Gg/yr (10%) and Bihar ~ 200 Gg/yr (9%). Similarly, in the wastewater management sector, Maharashtra is the largest contributor, responsible for approximately 202 Gg/yr (23%), with Gujarat, Uttar Pradesh, and Tamil Nadu contributing 97 Gg/yr (11%), 79 Gg/yr (9%), and 76 Gg/yr (8%), respectively. Collectively, Maharashtra accounts for the highest proportion of methane emissions from the waste management sector, with 14%, followed by Uttar Pradesh and Gujarat, with 12% and 7%, respectively. Further analysis indicates that more than half of the CH_4 emissions from the combined waste management sector originate from the top 100 districts across the country.
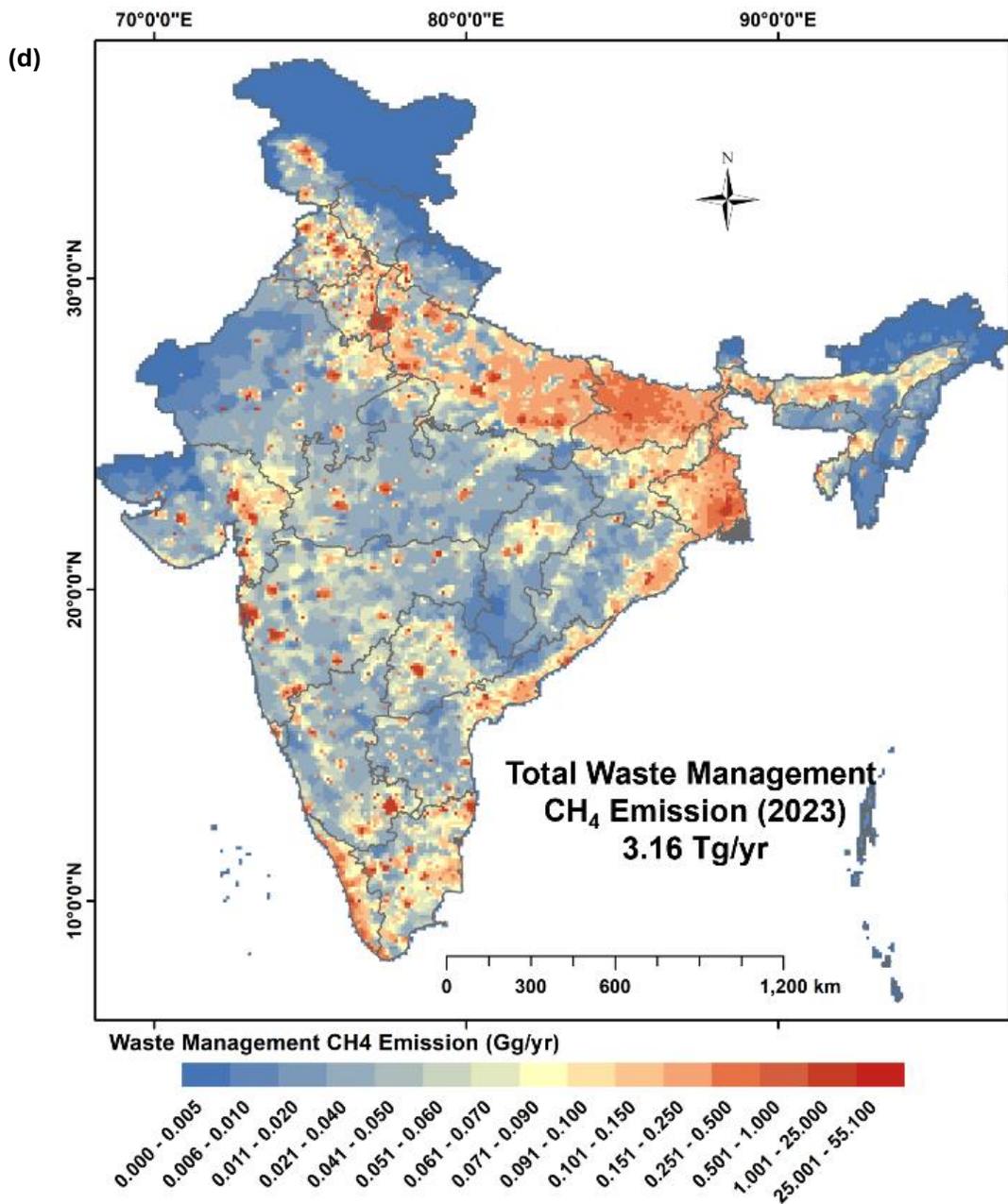
Methane is also primarily attributed to traditional fossil fuel consumption for energy, which includes coal mining, TPP, oil & gas extraction, refineries, and transportation activity. The states in the Central and Eastern India region, like Chhattisgarh, Odisha, Jharkhand, and Madhya Pradesh collectively emit two-thirds of CH_4 emissions due to intense coal mining activities and substantial coal reserves within these regions. Further, the presence of high-capacity oil refineries in states like Gujarat, Maharashtra, and Assam over Western, and North-Eastern regions is jointly responsible for half of the emissions from the Oil & Gas sector. Though a very small amount is emitted from TPP, Maharashtra, Madhya Pradesh, Chhattisgarh, Uttar Pradesh and Odisha contribute nearly 50% of emissions due to the presence of supercritical and ultra-supercritical power units. Similarly, significant transport-related emissions dominated over industrialized and populated states like Maharashtra, Rajasthan, Uttar Pradesh, Gujarat and Tamil Nadu, resulting in more than one-

third contribution. The inclusive emission from all the sectors shows that Gujarat, Maharashtra, and Assam emit one-third of total from fossil fuel-based activity, as shown in Figure 2(e). The Jamnagar in Gujarat emerges as the largest emitter in India, primarily due to the presence of the country's largest oil refinery.

(b)

Total Wetland CH_4
Emission (2023)
8.6 Tg/yr

Wetland CH4 Emission (Gg/yr)

0.000 - 0.005
0.006 - 0.010
0.011 - 0.025
0.026 - 0.050
0.051 - 0.075
0.076 - 0.100
0.101 - 0.250
0.251 - 0.500
0.501 - 0.750
0.751 - 1.000
1.001 - 1.250
1.251 - 2.500
2.501 - 5.000
5.001 - 15.000
15.001 - 25.000

(c)

Total Rice and Sugarcane Crop
Field CH$_4$ Emission (2023)
5.65 Tg/yr

Crop Field CH4 Emission (Gg/yr)

0.000 - 0.005
0.006 - 0.010
0.011 - 0.050
0.051 - 0.100
0.101 - 0.200
0.201 - 0.300
0.301 - 0.400
0.401 - 0.500
0.501 - 0.600
0.601 - 0.700
0.701 - 0.800
0.801 - 0.900
0.901 - 1.000
1.001 - 2.000
2.001 - 4.000

(d)

Total Waste Management
CH$_4$ Emission (2023)
3.16 Tg/yr

Waste Management CH4 Emission (Gg/yr)

0.000 - 0.005 0.006 - 0.010 0.011 - 0.020 0.021 - 0.040 0.041 - 0.050 0.051 - 0.060 0.061 - 0.070 0.071 - 0.090 0.091 - 0.100 0.101 - 0.150 0.151 - 0.250 0.251 - 0.500 0.501 - 1.000 1.001 - 25.000 25.001 - 55.100

(e)

Total Fossil Fuel
CH_4 Emission (2023)
3.35 Tg/yr

Fossil fuel Based CH4 Emission (Gg/yr)

0.000 - 0.001
0.002 - 0.005
0.006 - 0.007
0.008 - 0.010
0.011 - 0.012
0.013 - 0.015
0.016 - 0.017
0.018 - 0.020
0.021 - 0.025
0.026 - 0.050
0.051 - 0.100
0.101 - 1.000
1.001 - 10.000
10.001 - 100.000
100.001 - 186.000

(f)

Total Remaining Sector
CH$_4$ Emission (2023)
4.02 Tg/yr

Remaining Sector CH4 Emission (Gg/yr)

0.000 - 0.020 | 0.021 - 0.030 | 0.031 - 0.040 | 0.041 - 0.050 | 0.051 - 0.060 | 0.061 - 0.070 | 0.071 - 0.080 | 0.081 - 0.090 | 0.091 - 0.100 | 0.101 - 0.125 | 0.126 - 0.150 | 0.151 - 0.200 | 0.201 - 0.500 | 0.501 - 1.000 | 1.001 - 5.000 | 5.001 - 10.310

264   Fig 2: Sectoral methane emission from India in 2023 (a) Livestock, (b) Wetland, (c) Rice and

265   Sugarcane Crop Field, (d) Waste Management, (e) Fossil Fuel based Activities, (f)

266   Remaining sector.

267   In addition to the above sources, there are several sectors contributing to methane

268   emission, including organized and unorganized sectors like cooking activities, forest fires,

crop residue burning, brick kilns, crematories, and termites. Given the high rural population density in the Indo-Gangetic region compared to the rest of India, emissions from solid fuel and biomass-based cooking activities are notably higher, with Uttar Pradesh and Bihar alone responsible for more than one-fourth of these emissions (MoHA, 2011). Moreover, it is evident from the spatial maps that cities exhibit lower methane emissions due to lower livestock density, limited cropland areas, and improved cooking-fuel penetration as compared to semi-urban and rural regions. Whereas the similar sectors dominate in rural regions, leading to a shift of the hotspots. In accordance with the shifting cultivation practices in Northeastern India, forest fires are predominant sources of emissions in that region. Nearly two-thirds of CH_4 come from those Northeastern states, with Mizoram and Assam contributing ~ 139 Gg/yr (16%) and 112 Gg/yr (14%), respectively. Methane from crop residue burning is predominant in Punjab, responsible for nearly one-fourth of emissions from this sector. Three major agricultural states, Punjab, Madhya Pradesh, and Maharashtra, collectively emit approximately half of CH_4 emissions. The unorganized brick kilns sector is particularly found in Indo-Gangetic regions and Central India, where rural population density is high (MoHA, 2011). Though fly ash and concrete bricks are replacing mud bricks in urban and semi-urban areas, Northern states like Uttar Pradesh, Bihar, and Rajasthan still contribute nearly one-third of emissions from this sector. Traditional cremation practice , is another unorganized source of methane emissions, with the number of Hindu adherents in a state serving as a key regulatory factor. Uttar Pradesh and Maharashtra emit 15 Gg/yr of CH_4 out of 30 Gg/yr from the cremation of the deceased. Natural sources of CH_4, such as those from termites, have also been accounted for in this study. Emissions were estimated using forest area as a proxy, with dense forests in Jammu and Kashmir contributing to higher termite biomass and, consequently, greater CH_4 emissions. Jammu and Kashmir, Madhya Pradesh, and Odisha jointly contribute one-third of emissions from the termites. The state-wise top three dominating sectors and districts listed in Table S5 can be used for mitigation.

296   The grid-wise analysis depicts in Figure 3 that 11,740 (~40%) out of 30,185 grids

297   account for more than 1 Gg/yr of methane. The per-capita methane footprint of Indians is

298   found to be 27 kg, and the per square km area CH_4 burden is 11.6 tonnes.
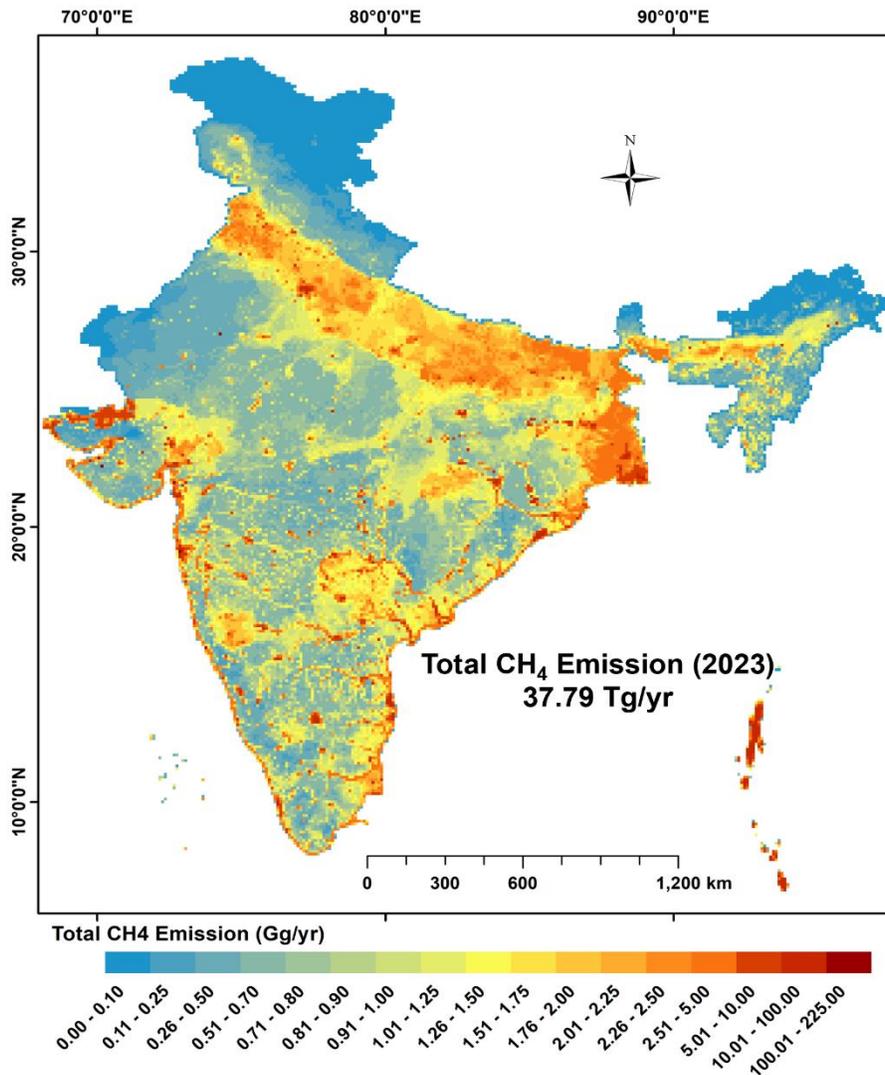
299

300   Figure 3: Spatial distribution of methane emission for India in 2023

301   **3.3 Intercomparison with previous studies**

302   The intercomparison of CH_4 emissions amongst the current study and previously published

303   papers gives insight into sector-specific contributions and reveals the concurrence and

304   discrepancies in findings over time. Notably, the national-scale comprehensive CH_4

305   emissions from various types of wetland systems and termites are reported for the first time

306 in this study. The latest estimate of methane emissions from India, as reported by EDGAR,
307 2023, amounts to 32.3 Tg/yr in 2022. The current study observes a consistent trend of
308 contribution to total emission across most sectors; however, the estimated emissions from
309 wastewater are remarkably high, exceeding the current estimate by more than sevenfold.
310 Unlike the current estimation, EDGAR's lack of regional emission factors has led to some
311 erratic estimates across various sectors. The current study identifies livestock as the largest
312 contributor, with methane emissions amounting to 13 Tg/yr. This figure is relatively
313 consistent with the EDGAR (2023), which reports a slightly higher value of 15.5 Tg/yr.
314 Previous studies, including those by Samal et al. (2024), Garg et al. (2011) and Garg et al.
315 (2006), reported emissions of 12.74 Tg/yr, 10.11 Tg/yr, and 10.62 Tg/yr, respectively, for base
316 years 2019, 2008, and 2005, indicating that livestock has consistently been recognized as a
317 major source of methane. The variation in estimates is attributable to adopted emission
318 factors, followed by differences in livestock population, feeding practices, and upgraded
319 manure management strategies employed in these studies. It is also important to note that,
320 the current estimate reveals that the agriculture sector comprising livestock and paddy
321 fields accounts for nearly half of the total CH_4 emission, which debunks the earlier reporting
322 of the agriculture sector attributed to two-thirds of total emissions from India (Garg et al.,
323 2001, 2006, 2011, EDGAR, 2023). Agricultural activities, particularly rice and sugarcane
324 cultivation, contribute 5.65 Tg/yr of methane according to the present study, aligning with
325 the understanding that India's status as a major rice producer significantly influences global
326 methane from this sector. However, the EDGAR (2023) inventory reports a lower emission
327 figure of 4.1 Tg/yr from agriculture, which may have resulted from emission factors
328 associated with irrigated versus rain-fed rice paddies. Garg et al. (2011) and Garg et al.
329 (2006) reported lower emissions from agriculture, at 3.88 Tg/yr and 4.02 Tg/yr, respectively.
330 These discrepancies may reflect changes in agricultural practices, water management
331 practices, or even climatic conditions that affect methane emissions from paddy fields.

332   In the current study, methane emissions from waste management are found to be
333 substantial, with 2.27 Tg/yr attributed to moderate solid waste management, including both
334 open waste burning and landfilling, and 0.9 Tg/yr from the treatment of residential and

335   industrial wastewater. By contrast, the EDGAR (2023) reports significantly higher emissions

336   from wastewater at 6.7 Tg/yr, yet lower rate from solid waste at 0.73 Tg/yr. This discrepancy

337   may stem from differences in the scope and methodologies employed in estimating

338   emissions from urban versus rural waste management practices. Garg et al. (2011, 2006)

339   reported methane of 1.71 Tg/yr and 0.96 Tg/yr from solid waste, and 0.17 Tg/yr and 0.67 Tg/yr

340   from wastewater for the years 2008 and 2005, respectively. Although these figures are lower

341   than those reported in the current study, they suggest a consistent trend in the contribution

342   of waste management to methane emissions over time. In the fossil fuel sector, including

343   emissions from coal mining, the current study estimates methane at 1.95 Tg/yr, with 0.78

344   Tg/yr specifically attributed to coal-mines. In comparison, EDGAR (2023) reports a lower

345   total of 0.7 Tg/yr from fossil fuel activities, suggesting potential underestimation or

346   differences in methodologies used to account for fugitive emissions. Garg et al. (2011, 2006)

347   reported 1.07 Tg/yr and 0.79 Tg/yr of methane emissions from fossil fuels, in the respective

348   studies, which are lower figures but still indicate a recognized contribution from this sector

349   over time. The current study estimates methane from biomass burning at 1.8 Tg/yr while

350   emissions from cooking activities contribute 1.42 Tg/yr. These figures align somewhat with

351   previous estimates, such as the 1.6 Tg/yr for biomass burning reported in EDGAR (2023).

352   However, estimates for cooking activities vary significantly across studies. For instance,

353   Garg et al. (2011) reported 2.23 Tg/yr, and Pandey et al. (2014) estimated 2.31 Tg/yr, both of

354   which are higher than the current study's figure. These variations could reflect differences

355   in the types of fuels considered, the efficiency of stoves, or regional cooking practices. The

356   intercomparison between the current and previous studies is illustrated in Figure 4.

359   Figure 4: Inter-comparison between current and previous studies.

360   In the current study, natural sources such as wetlands contribute 8.6 Tg/yr of
361   methane (the second most dominant contributor), a notable figure that has not been
362   explicitly detailed in many previous studies. The inclusion of wetlands as a significant
363   source in this study underscores a growing recognition of their importance in methane
364   inventories, likely due to advancements in methodologies for measuring emissions from
365   these ecosystems. While there is a consensus that India is a sink to substantial natural
366   sources of methane, the exact magnitude varies considerably across studies due to

367   differences in methodologies, emission factors used, and the scope of sectors considered.

368   Traditionally, livestock, agriculture, and solid waste have been acknowledged as major

369   contributors. However, the current study emphasizes the higher contributions from natural

370   sources like wetlands and man-made solid waste, reflecting an evolving understanding of

371   methane emissions in India. Moreover, earlier atmospheric methane inversion estimates by

372   Ganeshan et al (2017), Miller et al (2019), Chandra et al (2021) and Janardan et al (2024)

373   estimated 22 Tg/yr (2015), 35 Tg/yr (2015), 49 Tg/yr (2016), 29.24 Tg/yr (2020), respectively

374   over India. The direct quantitative comparison with this 2023 bottom-up inventory is

375   challenging due to varying base year-specific activity data and emission trends.

376   Nevertheless, our national total of 37.79 Tg/yr falls comfortably within this observed range

377   of inversion estimates, providing robustness to the inventory's magnitude.

378   **3.4 Uncertainty Estimation**

379   Although the current study on methane emissions in India is extensive, it

380   acknowledges inherent limitations in its estimations. The reliance on secondary activity

381   data and emission factors and the lack of sufficient details introduces a degree of

382   uncertainty. Despite these limitations, the study addresses crucial aspects of filling the data

383   gap and providing support to climate modeling and will be instrumental in identifying

384   methane hotspots across the country. It will also enhance the quantification of the roles

385   played by various natural and anthropogenic sources in the country, thereby assisting

386   policymakers in implementing advanced technological mitigation strategies to reduce

387   methane emissions. The uncertainty of all the individual sectors lies in the range of ± 32-

388   161% where the natural sources like wetlands and termites have higher uncertainty levels

389   of ± 137% and ±161% respectively. The uncertainty estimated from waste management is

390   restricted to ± 33%. The overall uncertainty of the current CH_4 emission inventory is found to

391   be ± 59%. The sector-specific uncertainty level is illustrated in Figure 5. The comparatively

392   higher uncertainty associated with certain source categories, particularly wetlands and

393   termites, primarily reflects deficiencies in high-resolution activity data and the limited

394   availability of region-specific and country-wise emission factors. These natural sources are

inherently difficult to constrain due to strong spatial and seasonal variability and their dependence on environmental drivers. Although sectoral uncertainties may affect the magnitude of emissions at localized scales, they do not compromise the integrity of the broader spatial patterns. Most of the previous studies haven't reported the sector-wise uncertainties for India specifically and global studies like Saunois et al. (2025) have reported the uncertainty of ~45% for Southeast Asia as a whole. This is the mean uncertainty calculated for all other nations in Southeast Asia, including India, where the uncertainty associated with large country like India is unclear. Solazzo et al. (2021) presented the sectoral uncertainties of CH_4 in the EDGAR estimation for India. The reported uncertainties in the Energy: fuel consumption sector were found to be 223%, followed by Oil & Gas (139%), Waste (107%), Solid fuels (57%), Industrial processes and product use (42%), and Agriculture (42%). However, the uncertainty reported here is improved with the use of regional activity data, diverse proxy data and regional scale sectoral emission factors. The uncertainty shoots up with the inclusion of natural sources like emissions from Wetlands (Inland wetland, Coastal wetland & Mangroves) and Termites. It is observed that uncertainty associate with small sectors like coal mining, forest fire is high as compared to major traditional sectors like Livestock and paddy field. Besides these sectors, the overall anthropogenic emission uncertainty is found to be ~44%, improving the reliability of developed present inventory and robustness of the emission dataset. The higher uncertainty for various sources, including natural sources, is due to the paucity of updated technological emission factors. With higher emissions and higher uncertainty of the wetland sector, it alone drives the uncertainty upward.
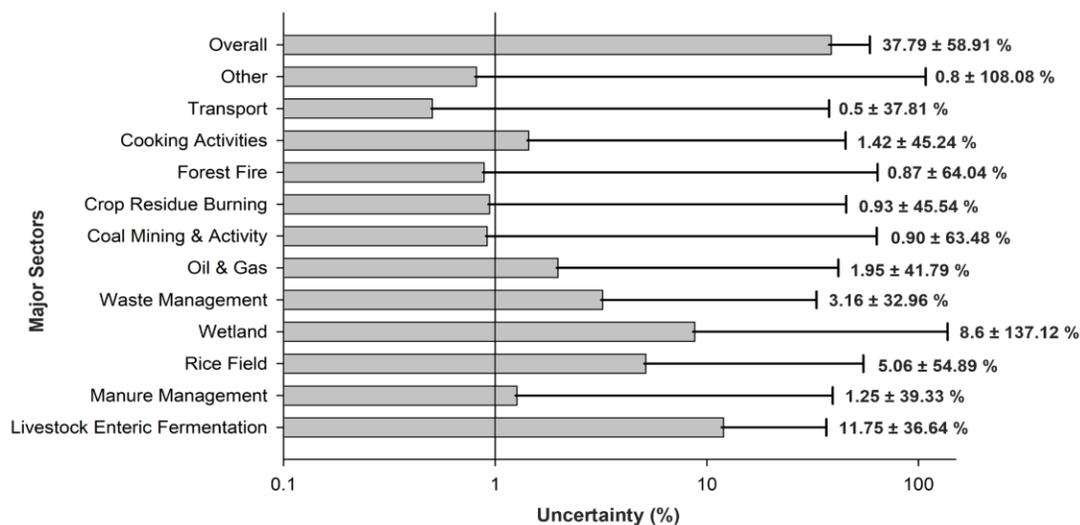
417

418   Figure 5: Sector-wise uncertainty estimation (Semi-log plot)

419   **4. Conclusion**

420   The present study not only addresses the reporting of the most recent gridded

421   methane dataset over India by synthesizing country-specific 25 distinct major and minor

422   natural and anthropogenic sources but also fills the gap in the country's methane budget.

423   The total methane emissions for the most recent base year, i.e., 2023, are found to be 37.79

424   Tg/yr, with approximately 75% attributed to anthropogenic activities. Methane data will be

425   a crucial input not only for climate modeling but also for understanding India's contribution

426   to the global methane budget. The study reports many sub-sectors of wetlands and

427   termites, which are the first-of-its-kind to strengthen the understanding of methane

428   emissions in India. This newly developed state-of-the-art, high-resolution gridded methane

429   dataset would be valuable input for climate models to optimize simulation.

430   **Funding:**

431   This full research work did not receive any specific grant from funding agencies in the public,

432   commercial, or not-for-profit sectors.

433   **Conflicts of interest**

434 The authors declare that they have no known competing financial interests or personal

435 relationships that could have appeared to influence the work reported in this paper.

436 **Data availability statements**

437 The data supporting this article has been included as part of the Supplementary Information.

438 The emission dataset can be accessed through the open-access data repository Zenodo.

439 Methane Emission Data [Dataset]. https://doi.org/10.5281/zenodo.14089138. (Sahu, S. K.,

440 2024).

441 **Author contributions:**

442 AM wrote the whole paper and analyzed and plotted the scientific data for necessary

443 discussion. PM and PS helped in the analysis and provided useful insight. GB and RJ

444 reviewed the article and suggested a justified conclusion, and SKS conceived the present

445 idea, analyzed the data and reviewed the manuscript.

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