

1 **Reporting of Gridded (0.1°X0.1°) Methane Emission Dataset for India to**  
2 **Redefine Global Climate Studies; 2023**

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12 **Abstract**

13 Methane (CH<sub>4</sub>) is a predominant climate-forcing agent and has become a focal point of  
14 global climate discussions, owing to its significant contribution to atmospheric warming.  
15 The ambiguity surrounding the relative contributions of various natural and anthropogenic  
16 sources, coupled with associated uncertainties, poses significant challenges to assessing  
17 methane emissions in developing nations like India. To address these challenges and better  
18 understand the methane-emitting sources, this study presents a comprehensive high-  
19 resolution gridded (0.1°×0.1°) inventory of CH<sub>4</sub> emission by including 25 distinct  
20 anthropogenic and natural sources in India for 2023 by adopting the IPCC bottom-up  
21 approach. The estimated CH<sub>4</sub> over India is 37.79 Tg/yr, which will redefine the contribution  
22 of various sources. The agriculture sector contributed ~50% followed by wetlands (8.6%),  
23 fossil fuel and waste management. This study reports the first-ever comprehensive  
24 emissions from natural sources like wetlands and termites. The Indo-Gangetic Plain (IGP)  
25 and coastal states show elevated emissions with Uttar Pradesh contributing the highest  
26 (10.8%) followed by Gujarat (9.4%), and Maharashtra (8.6%). However, surprisingly cities  
27 exhibit lower CH<sub>4</sub> as compared to other semi-urban/rural regions. This developed dataset  
28 can be a valuable input to optimize the climate study by filling the data gap, enabling  
29 policymakers to formulate various mitigation measures. The emission dataset can be  
30 accessed through the Zenodo repository <https://doi.org/10.5281/zenodo.14089138> (Sahu S.  
31 K., 2024).

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

## 34 1. Introduction

35 Methane (CH<sub>4</sub>) is the second most abundant and potent greenhouse gas (GHG) in the  
36 atmosphere, after Carbon Dioxide (CO<sub>2</sub>) (European Commission, 2023). Its ability to trap  
37 heat by absorbing outgoing thermal infrared radiation is 28 times more than CO<sub>2</sub> resulting in  
38 16-25% of atmospheric warming to date (Rosentreter et al., 2021). The surface dry-air mole  
39 fraction of atmospheric CH<sub>4</sub> has escalated to 1931 ppb, nearly 2.6 times the level recorded  
40 in the preindustrial era of 1750 (NOAA, 2024). The significant rise in CH<sub>4</sub> concentrations  
41 necessitates urgent mitigation of methane emissions, given its potential to induce near-  
42 term climatic changes and its involvement in the formation of tropospheric ozone.

43 The global CH<sub>4</sub> emissions in 2017 were estimated through the bottom-up approach  
44 amounted to be ~747 (602–896) Tg/yr, primarily contributed by anthropogenic sources  
45 (Saunois et al., 2020). China is responsible for the highest emissions with more than 20% of  
46 the global anthropogenic CH<sub>4</sub>, followed by South Asia (13%), Southeast Asia (8%), and the  
47 United States of America (USA) (7%) (Saunois et al., 2020). The anthropogenic emissions are  
48 attributed to various sources like livestock, agriculture, solid waste, wastewater  
49 management, fossil fuel production, biomass burning, etc. Given the extensive domestic  
50 and agricultural practices such as livestock and vegetative culture, South Asian regions are  
51 a global hotspot of CH<sub>4</sub> emissions (Saunois et al., 2020). Given the diversity of methane  
52 sources across the world, the real challenge lies in identifying the country-specific prevailing  
53 and predominant sources that may have a disproportionate contribution to the national  
54 total emissions. Understanding regional sources in developing nations like India is  
55 paramount, where the spatial diversity of sources is much more complex, to identify and  
56 quantify methane emissions comprehensively. As per India's third Biennial Update Report  
57 to the United Nations Framework Convention on Climate Change (UNFCCC), Indian  
58 agriculture sectors contributed nearly 75% of national total methane emissions in 2016  
59 (excluding Land Use, Land Use Change, and Forestry) (MoEFCC, 2021). Owing to this report,  
60 the Government of India (GoI) has implemented numerous policies like the National  
61 Livestock Mission, Gobar-Dhan Scheme, National Biogas and Organic Manure Programme,

62 National Mission for Sustainable Agriculture, National Innovations in Climate Resilient  
63 Agriculture, and Swachh Bharat Mission under Nationally Determined Contribution (NDC)  
64 to curtail CH<sub>4</sub> like GHGs. However, India has not signed the 'Global Methane Pledge'  
65 proposed by the European Union and the United States of America to target a 30% reduction  
66 in global methane emissions from 2020 levels by 2030. Since, India is one of the largest  
67 producers and exporters of agricultural products, particularly from paddy cultivation and  
68 livestock farming, addressing food security both domestically and globally is crucial.  
69 Consequently, the CH<sub>4</sub> from these sources are viewed as survival emissions rather than  
70 luxury emissions (MoEFCC, 2023). So, to account for the efficacy of these policy  
71 interventions, we need to have comprehensive updated sector-specific methane emission  
72 data and the emission inventory will help us keep track of sectoral emissions and our  
73 performance compared to other nations in curbing methane pollution.

74 National multi-sectoral CH<sub>4</sub> emissions were last reported by Garg et al. (2011) for the  
75 base year 2008 at the district level (Garg et al., 2011). Although some global inventories have  
76 reported CH<sub>4</sub> emissions from India in recent years, they primarily relied on Tier I top-down  
77 approach, resulting in inconsistent estimations for several sectors (EDGAR, 2023, Saunio  
78 et al., 2016). Given the lack of systematic reporting of sector-specific high-resolution activity  
79 data, there is a huge challenge in filling the data gaps that estimate comprehensive sectoral  
80 CH<sub>4</sub> emissions in India. Parasher et al. (1996) reported 4 Tg/yr of CH<sub>4</sub> from paddy fields for  
81 the first time in 1991. Since then, various studies focusing on specific sectors have been  
82 conducted, with livestock, solid waste management, and biomass burning being the most  
83 extensively examined sectors concerning CH<sub>4</sub> emission. The CH<sub>4</sub> from the livestock sector  
84 have ranged between 7.26 Tg/yr and 15.5 Tg/yr from 1990 to 2022 (EDGAR, 2023, Garg et al.,  
85 2001). Notably, there have been only four national multi-sectoral emission inventories  
86 during this period, all of which were conducted by Garg et al. (2001, 2006, 2011), where the  
87 estimated methane ranges from 17.05 Tg/yr to 20.57 Tg/yr for 1990 and 2008. Apart from  
88 livestock and paddy, the waste management sector, encompassing solid waste burning and  
89 landfilling, and both domestic and industrial wastewater sectors, is also responsible for a  
90 significant share of CH<sub>4</sub>. Similarly, activities based on biomass and fossil fuels contribute

91 substantially to national CH<sub>4</sub> emissions. However, the lack of updated sector-specific  
92 activity data and the coarse spatial distribution of emissions render these estimates  
93 incompatible, and huge data gaps lead to large uncertainties in climate studies.  
94 Furthermore, it has been observed that many natural and unmonitored sources were  
95 excluded from earlier estimates, adding to the uncertainty in identifying regional hotspots.  
96 The temporal and spatial diversity of sources outlines the necessity of an updated emission  
97 inventory (Sahu et al., 2023, Mangaraj et al., 2022a, 2022b, 2024a, 2024b, Janardan et al., 2024).  
98 This study provides a comprehensive development and spatial analysis of sectoral methane  
99 (CH<sub>4</sub>) hotspots across India at a fine resolution of 0.1° × 0.1° by incorporating 25 natural and  
100 anthropogenic sources for the year 2023. This study also offers strategic targets for further  
101 climate research. The newly developed methane emission database will be invaluable, not  
102 only for advancing regional climate research by filling the data gap in the country but also as  
103 an essential tool for policymakers in formulating mitigation strategies.

## 104 **2. Methodology**

105 The present attempt is intended to quantify the recent methane emission budget for India in  
106 2023. The study targets 25 natural and anthropogenic sources, including livestock, rice crop  
107 fields, wetlands, oil & gas, solid waste, wastewater, and biomass burning, termite,  
108 transportation etc., which are the significant emission sectors in the country. The source-  
109 specific emissions are estimated in accordance with the IPCC tier II/III country-specific  
110 technological emission factors-based bottom-up approach methodology presented in the  
111 supplementary file (Sahu et al., 2023a, 2023b, 2021, 2024, Mangaraj et al., 2022a, 2022b,  
112 2024a, 2024b, Sahoo et al., 2024, Samal et al., 2024). The importance of the bottom-up  
113 approach lies in the compilation of high-resolution activity data (AD) and regional emission  
114 factors (EF). The AD entails gathering comprehensive information at each source level, such  
115 as species-wise population data of livestock, water regime-wise crop area and cropping  
116 pattern for rice and sugarcane cropping, high-resolution spatial information of each source  
117 for thermal power plants (TPP), wastewater treatment facilities, type of wetland area for  
118 wetlands, vehicular type, volume of traffic and driving pattern, technology used, age of

119 vehicles, fuel use for transportation, waste and wastewater generation waste management,  
120 temperature data for wetland, etc. Similarly, country-specific EF is a pivotal component of  
121 developing emission inventory as the sensitivity of the EF decides the uncertainty in the  
122 estimation and leads to inappropriate spatial patterns of gridded emission. This study  
123 ratified the country-specific proxy-level technological EFs for estimation. The details of AD  
124 and EF are presented in supplementary Tables S1, S2, S3, and S4 respectively. The bottom-  
125 up framework relies on an emission factor-based formulation, in which emissions from each  
126 source category are estimated as a function of activity data, technology-specific emission  
127 factors, fuel use, and emission control efficiencies. The sectoral total emissions will then be  
128 estimated using established formulations, including sector-specific fuel-wise technology-  
129 based equations as per equation (1). The emission from the road transport sector  
130 specifically has been calculated as per the following equation: -

$$131 \quad E = \sum_a \sum_b F_{a,b} [\sum_c E_{f_{a,b,c}} A_{a,b,c}] \quad (1)$$

132 where a, b, c = sector, fuel type, technology; E= Total amount of Emission; F = sector-wise  
133 fuel amount; Ef = Country specific technology emission factors; A = amount of fuel  
134 associated with particular technology where  $\sum A = 1$  for each kind of fuel and sector.

135 The detailed methodology, uncertainty estimation, and spatial allocation of emission are  
136 presented in the supplementary file.

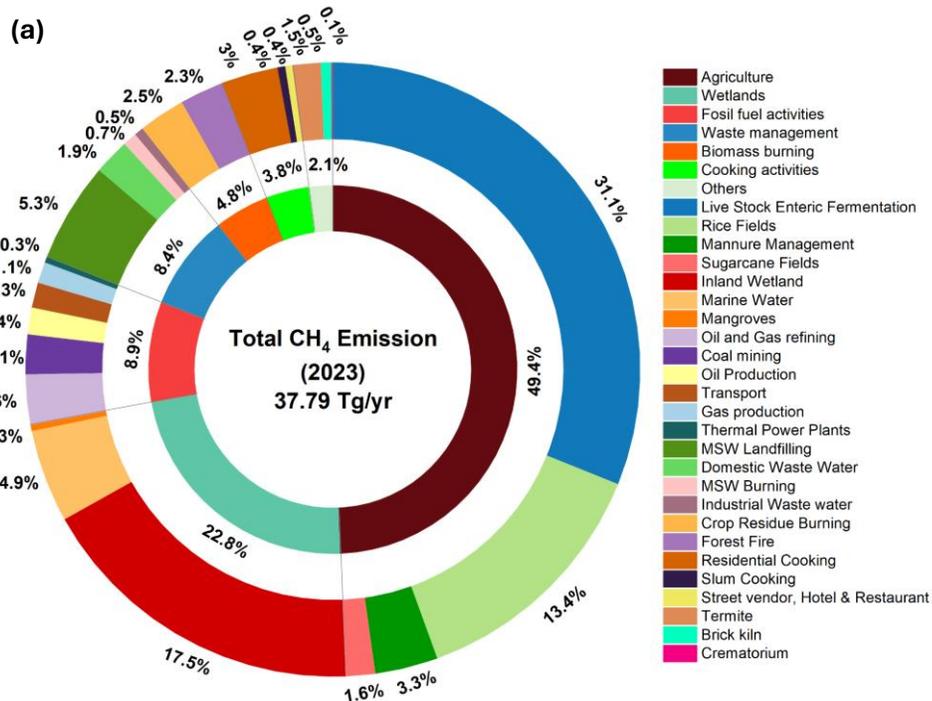
### 137 **3. Results and discussion**

#### 138 **3.1 Sectoral contribution to total CH<sub>4</sub> emission**

139 The total methane emissions, estimated from 25 types of sources (natural and  
140 anthropogenic) in India, is ~37.79 Tg/yr in 2023. The agricultural sector, encompassing both  
141 livestock and crop fields, emerged as the predominant contributor, accounting for nearly  
142 half (~49%) of the nation's methane emissions. Specifically, livestock enteric fermentation  
143 alone is responsible for approximately one-third of agricultural sector emissions, while rice  
144 crop fields contributed about 13%. Wetlands constituted the next significant source,  
145 contributing more than one-fifth (8.6 Tg/yr) of the national total. This is followed by

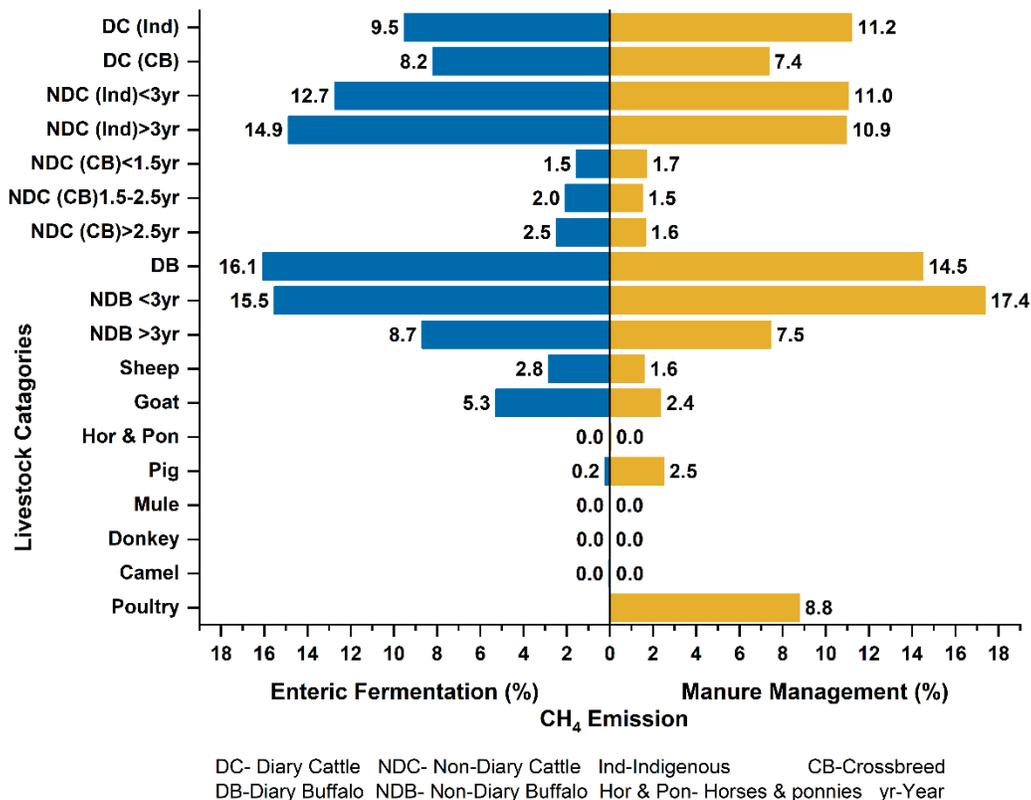
146 emissions from fossil fuel-based activities, which accounted for approximately 9% (3.35  
 147 Tg/yr), waste management (~8%), biomass burning (~5%), cooking activities (~4%), and  
 148 other miscellaneous sources comprising about ~2% of the total emissions, as illustrated in  
 149 Figure 1 (a).

150 In the case of livestock, cattle are the major contributors, emitting 6.03 Tg/yr (~51%)  
 151 of methane due to enteric fermentation. Notably, indigenous cattle are identified as the  
 152 largest contributors within this category, responsible for ~37% of the emissions, followed by  
 153 crossbred cattle (~14%). It is observed that non-dairy cattle contributed more significantly  
 154 to methane (~33%) than dairy cattle (~18%). Buffaloes also contributed a substantial ~40%  
 155 to the emissions, with non-dairy buffaloes being the primary emitters (~24%), followed by  
 156 goats (~5%), sheep (~3%), and other livestock species as shown in Figure 1 (b). Moreover, a  
 157 similar trend is observed in manure management, where cattle are the leading contributors,  
 158 responsible for ~45% of methane emissions, followed by buffaloes (~39%), poultry (~8%),  
 159 pigs (~2.5%), goats (~2%), and other species.



160

(b)



162

163 Fig 1: (a) Sectoral Contribution of CH<sub>4</sub> emission (% total), (b) Livestock (% of sector)  
 164 in 2023

165 Wetlands have emerged as the second largest source of CH<sub>4</sub> emissions in India,  
 166 where the inland wetlands contribute the highest (~17%) followed by rice fields (~13%). The  
 167 present attempt examines the comprehensive coastal CH<sub>4</sub> budget, revealing that the marine  
 168 wetlands in coastal areas emit roughly 1.85 Tg/yr. Additionally, the sensitive mangrove  
 169 ecosystems release 0.84 Tg/yr into the atmosphere. The emission analysis also included  
 170 data on rice and sugarcane cropping areas, as well as irrigation statistics, retrieved from the  
 171 Ministry of Agriculture and Farmers’ Welfare. The findings indicate that flooded agricultural  
 172 lands contribute more significantly to methane emissions compared to single-irrigation or  
 173 drought-prone regions, with rice fields alone responsible for 5.65 Tg/yr of CH<sub>4</sub>. In addition to  
 174 wetlands and agricultural lands, MSW landfills are identified as a major source of methane

175 emissions, releasing approximately 2 Tg/yr. This is followed by cooking activities (~1.4 Tg/yr)  
176 where residential cooking in both rural and urban localities, slum areas, as well as  
177 commercial cooking activities do contribute a good fraction.

178 Further, methane emissions from coal mining and oil and gas extraction processes  
179 collectively amount to 1.74 Tg/yr. Additionally, crude oil refining processes contribute  
180 another 1 Tg/yr of CH<sub>4</sub>. The transport and TPP sector, which rely on these fossil fuels, emit  
181 an extra 0.62 Tg/yr. Smaller, but noteworthy, contributions come from fugitive sources like  
182 brick kilns and crematories, emitting 0.23 Tg/yr. Lastly, natural methane emissions from  
183 termites were also accounted for, contributing approximately 1.5% to the total CH<sub>4</sub> in 2023.

### 184 **3.2 Spatial variability in CH<sub>4</sub>**

185 The spatially resolved estimated CH<sub>4</sub> emissions are crucial in identifying precise dominating  
186 sources over particular regions. The resolution of the inventory is a significant parameter, as  
187 it allows for the precise identification of hotspots and associated dominating sectors  
188 contributing to high emissions. As illustrated in Figure 2(a), CH<sub>4</sub> from livestock are  
189 particularly predominant in Western India, the Indo-Gangetic Plain, and the Deccan  
190 Plateau. Specifically, the province of Uttar Pradesh contributed the most (~16%) to CH<sub>4</sub>  
191 emissions from the livestock sector as it outnumbered the other states in cattle and buffalo  
192 population. It is then followed by Rajasthan (~10%), Madhya Pradesh (~9%), Bihar (~7%) and  
193 Gujarat (~7%). It is very interesting to note that the top 160 districts (out of 785 districts) are  
194 responsible for nearly half of the livestock CH<sub>4</sub> emissions with Banas Kantha district in  
195 Gujarat being the largest emitter with ~99 Gg/yr.

196 Natural sources like wetlands, especially inland water bodies that constitute rivers,  
197 lakes, and ponds are the second largest sources of CH<sub>4</sub> emissions and are well scattered  
198 across the country. Figure 2(b) reveals that Eastern India is more susceptible to such  
199 emissions induced by inland water bodies compared to Western India, largely due to the  
200 eastward flow of most major river systems towards the Bay of Bengal. The Ganges,  
201 Brahmaputra, Mahanadi, and Godavari river basins, which span the Eastern, Northeastern,

202 Deccan, and Southern peninsular regions, are identified as significant sources of wetland-  
203 based CH<sub>4</sub> emissions. As some of the notable rivers originated from the Western Ghats and  
204 flowed east, the Southern peninsula and the Deccan plateau region became a web of CH<sub>4</sub>  
205 emission, as presented in Figure 2(b). However, Gujarat comes out as the highest with 1205  
206 Gg/yr (~18%) emitting state from inland water bodies for the Rann of Kachchh and the  
207 presence of significant water bodies like Narmada, Tapti and Sabarmati rivers and several  
208 lakes and ponds. In addition to it, this study also encompasses emissions from coastal and  
209 mangrove forest emissions. Although the Andaman and Nicobar Islands have the largest  
210 coastline in India, Gujarat leads in CH<sub>4</sub> emissions from coastal water bodies, contributing  
211 approximately 506 Gg/yr (27%), primarily due to the presence of numerous coastal creeks.  
212 Further, West Bengal is the highest emitter of CH<sub>4</sub> from the mangrove ecosystem with 65.1  
213 Gg/yr (52%) due to the Sundarbans delta region. Hence, overall, Gujarat emerges as the  
214 highest emitting state from wetlands, accounting for approximately 20%, followed by the  
215 Andaman and Nicobar Islands (12%), Andhra Pradesh (12%), Maharashtra (12%), and  
216 Odisha (10%), It is noteworthy that the top 25 districts contribute to more than half of the  
217 total CH<sub>4</sub> from wetlands, with the Kachchh district of Gujarat being the largest emitter from  
218 the wetland sector. This is followed by North and Middle Andaman (Andaman and Nicobar  
219 Islands), South 24 Parganas (West Bengal), South Andaman (Andaman and Nicobar  
220 Islands), and Nellore (Andhra Pradesh).

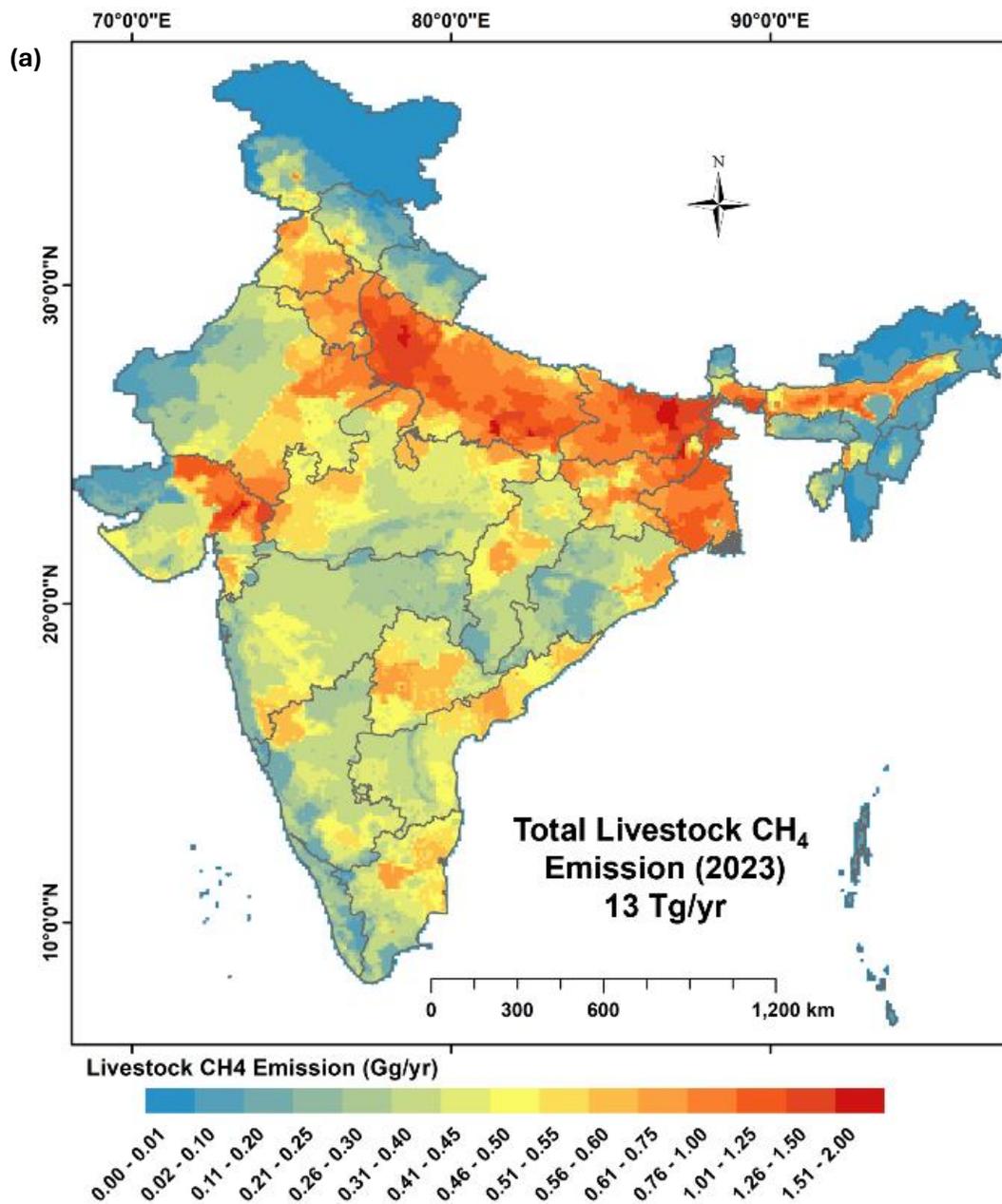
221 The spatial distribution of CH<sub>4</sub> from cropland exhibits a pattern closely aligned with  
222 that of inland wetlands, particularly in regions where intensive cropping practices are  
223 observed near freshwater bodies and experiencing monsoons. Indo-Gangetic basin,  
224 Brahmaputra basin, East Coastal, and the Deccan plateau states are the major rice and  
225 sugarcane-producing states, as shown in Figure 2(c). Telangana, Uttar Pradesh, and West  
226 Bengal are the largest rice-producing states while Uttar Pradesh, Maharashtra, and  
227 Karnataka lead in sugarcane production (MoA & FW, 2024). Consequently, Uttar Pradesh  
228 emerges as the highest contributor to CH<sub>4</sub> from crop fields, accounting for approximately  
229 1022 Gg/yr (18%) of the total, followed by West Bengal 663 Gg/yr (12%), Chhattisgarh 435  
230 Gg/yr (8%), Bihar 418 Gg/yr (7%) and Telangana 409 Gg/yr (7%). Notably, over 50% of total

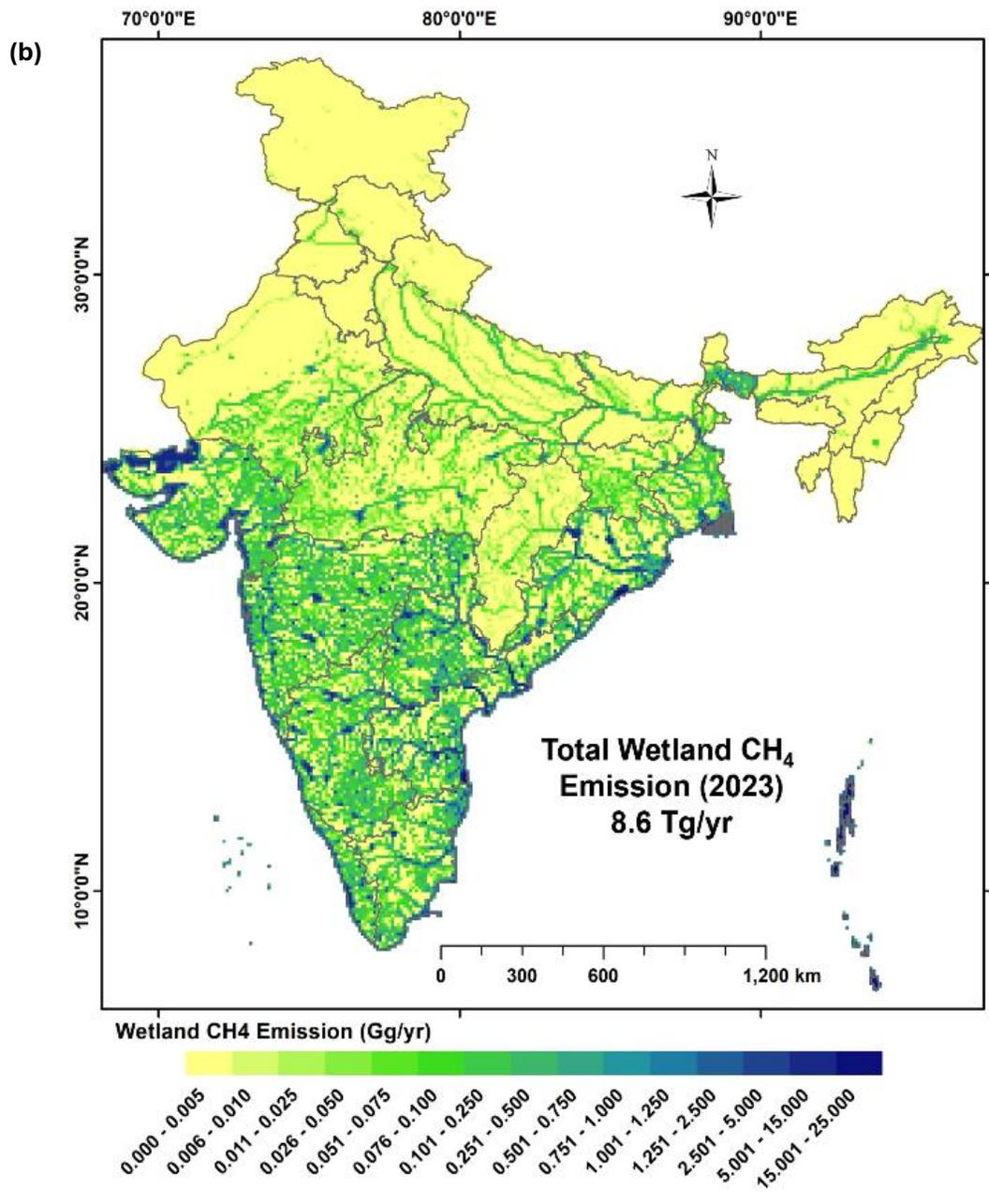
231 emissions from crop fields originate from the top 90 districts out of which Nalgonda  
232 (Telangana), Paschim Medinipur (West Bengal) and Karimnagar (Telangana) are the leading  
233 emitters.

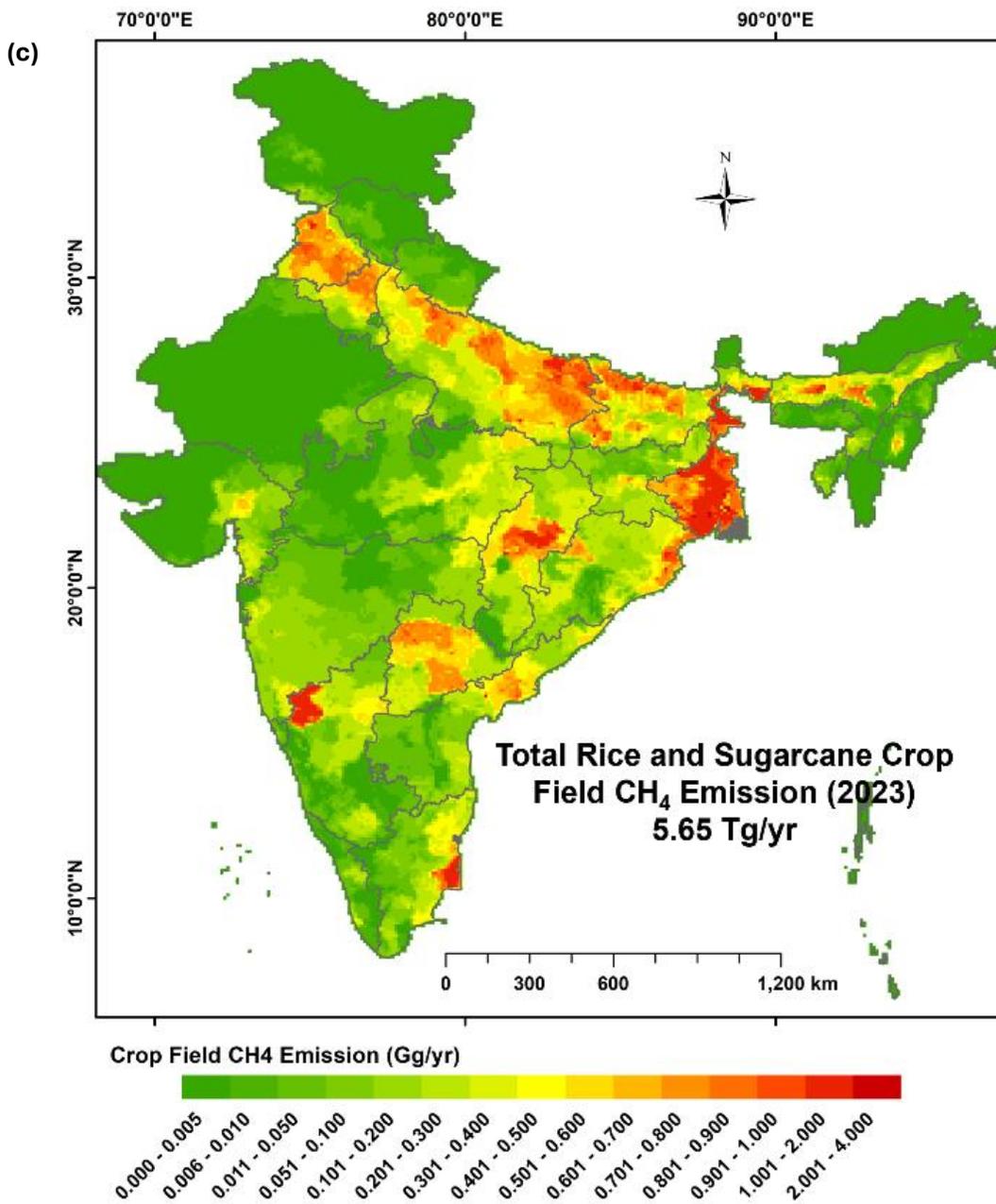
234 Waste management poses a significant challenge in developing India, where the  
235 burden of waste and its associated pollution has adversely affected urban living conditions.  
236 It is evident from Figure 2(d) that the Indo-Gangetic Basin states are more susceptible to high  
237 emissions than rest India. In solid waste management like burning and landfilling, Uttar  
238 Pradesh contributes ~ 303 Gg/yr (13%), followed by Maharashtra ~ 229 Gg/yr (10%) and Bihar  
239 ~ 200 Gg/yr (9%). Similarly, in the wastewater management sector, Maharashtra is the  
240 largest contributor, responsible for approximately 202 Gg/yr (23%), with Gujarat, Uttar  
241 Pradesh, and Tamil Nadu contributing 97 Gg/yr (11%), 79 Gg/yr (9%), and 76 Gg/yr (8%),  
242 respectively. Collectively, Maharashtra accounts for the highest proportion of methane  
243 emissions from the waste management sector, with 14%, followed by Uttar Pradesh and  
244 Gujarat, with 12% and 7%, respectively. Further analysis indicates that more than half of the  
245 CH<sub>4</sub> emissions from the combined waste management sector originate from the top 100  
246 districts across the country.

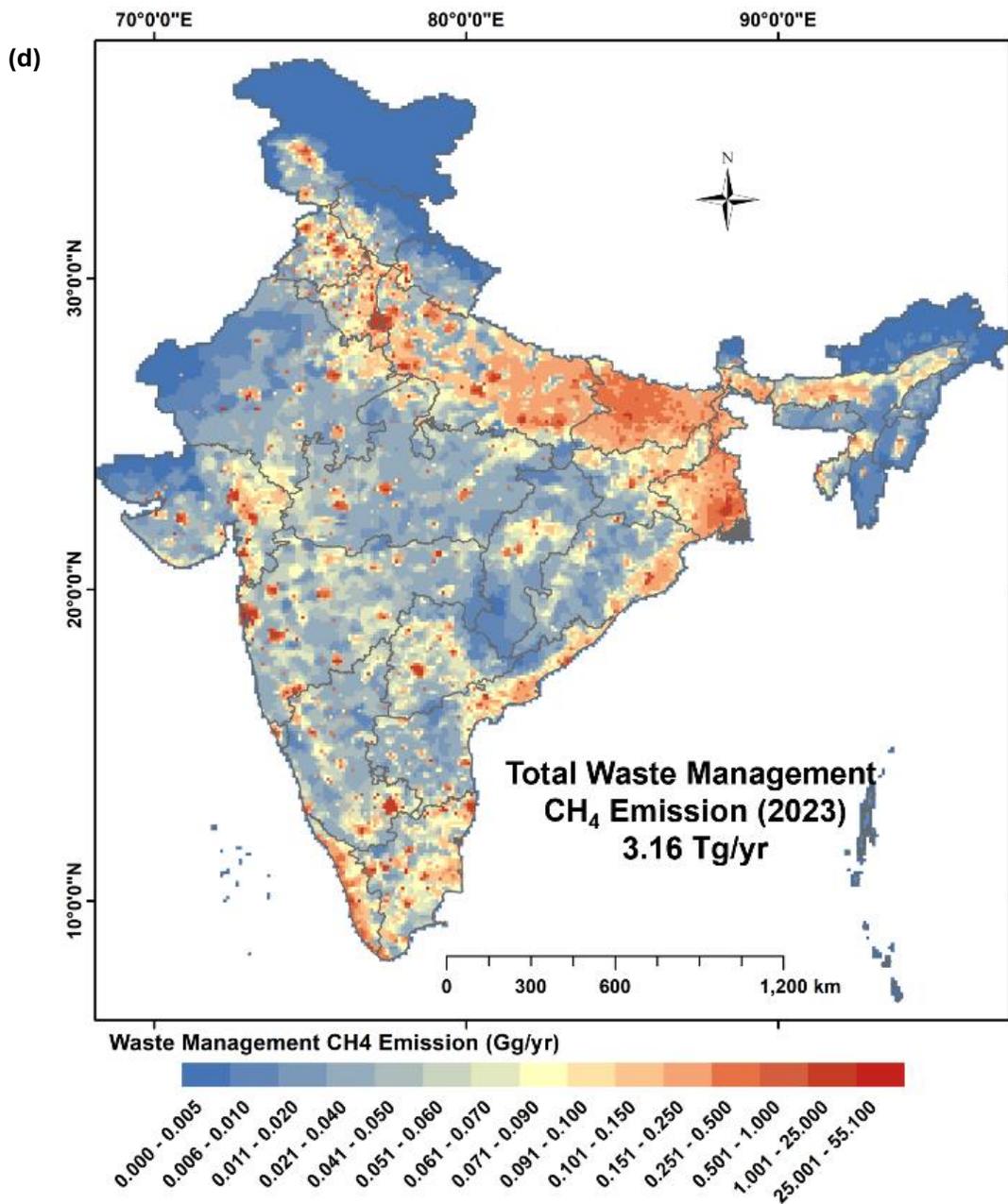
247 Methane is also primarily attributed to traditional fossil fuel consumption for energy,  
248 which includes coal mining, TPP, oil & gas extraction, refineries, and transportation activity.  
249 The states in the Central and Eastern India region, like Chhattisgarh, Odisha, Jharkhand, and  
250 Madhya Pradesh collectively emit two-thirds of CH<sub>4</sub> emissions due to intense coal mining  
251 activities and substantial coal reserves within these regions. Further, the presence of high-  
252 capacity oil refineries in states like Gujarat, Maharashtra, and Assam over Western, and  
253 North-Eastern regions is jointly responsible for half of the emissions from the Oil & Gas  
254 sector. Though a very small amount is emitted from TPP, Maharashtra, Madhya Pradesh,  
255 Chhattisgarh, Uttar Pradesh and Odisha contribute nearly 50% of emissions due to the  
256 presence of supercritical and ultra-supercritical power units. Similarly, significant  
257 transport-related emissions dominated over industrialized and populated states like  
258 Maharashtra, Rajasthan, Uttar Pradesh, Gujarat and Tamil Nadu, resulting in more than one-

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

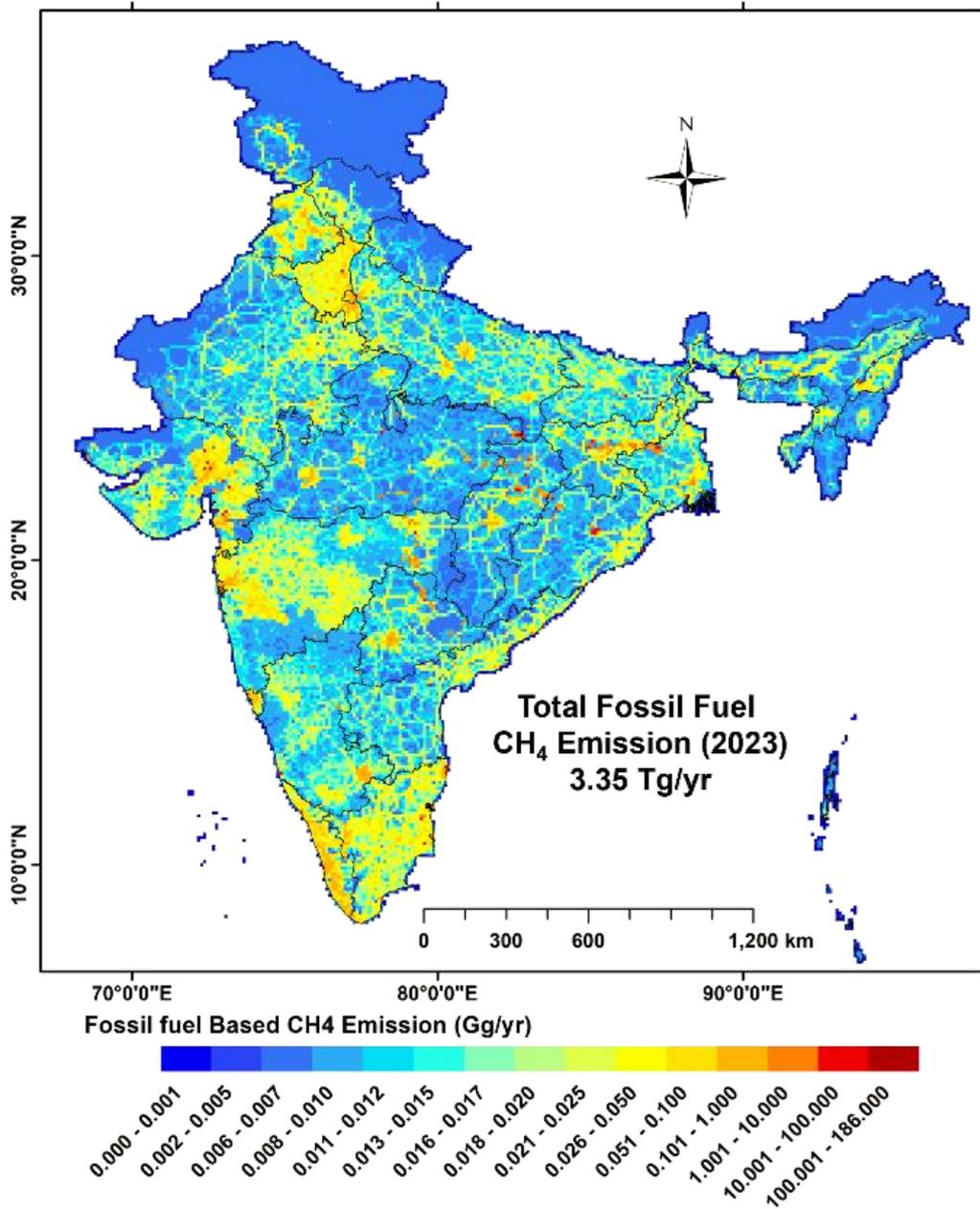


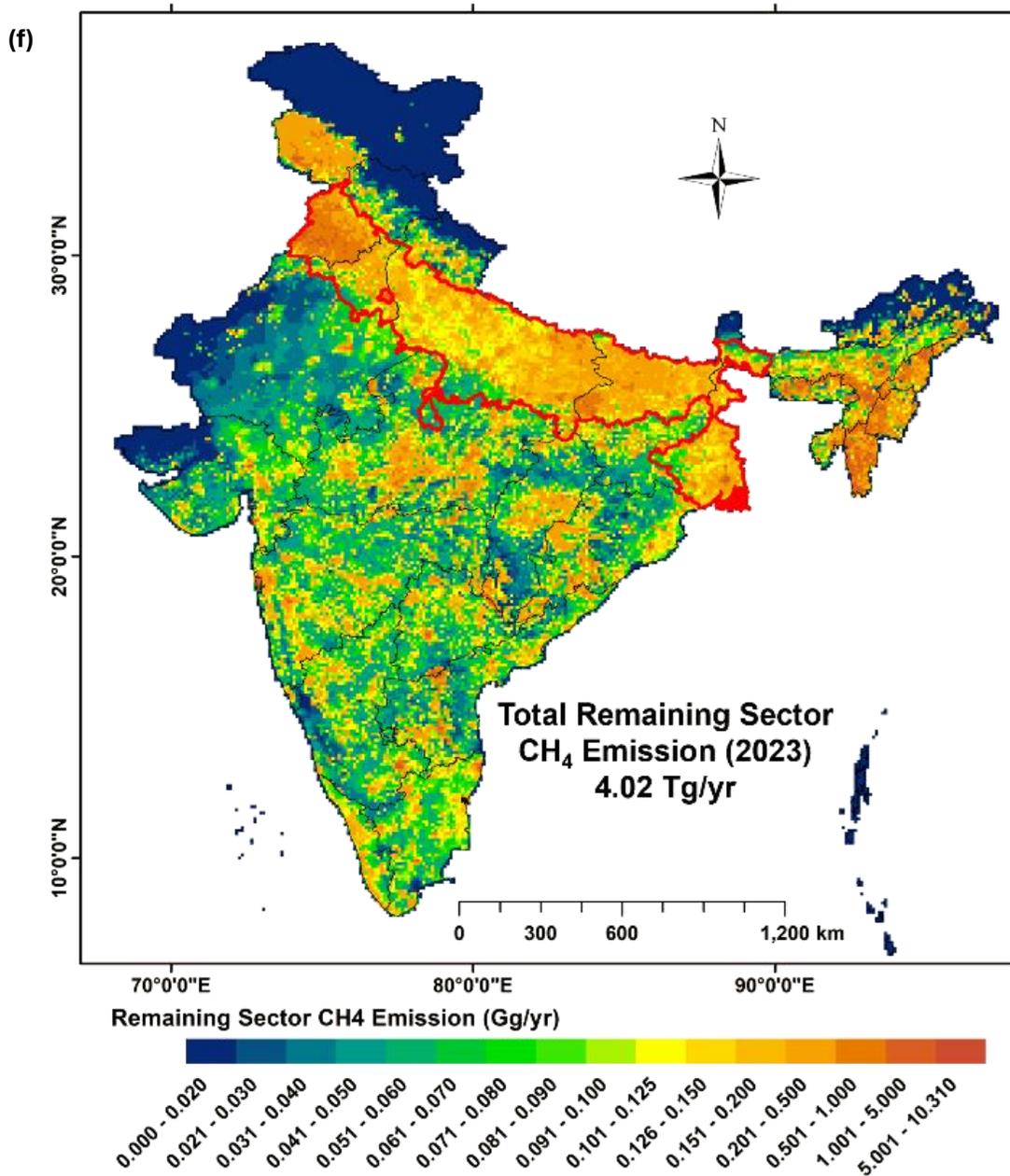






(e)



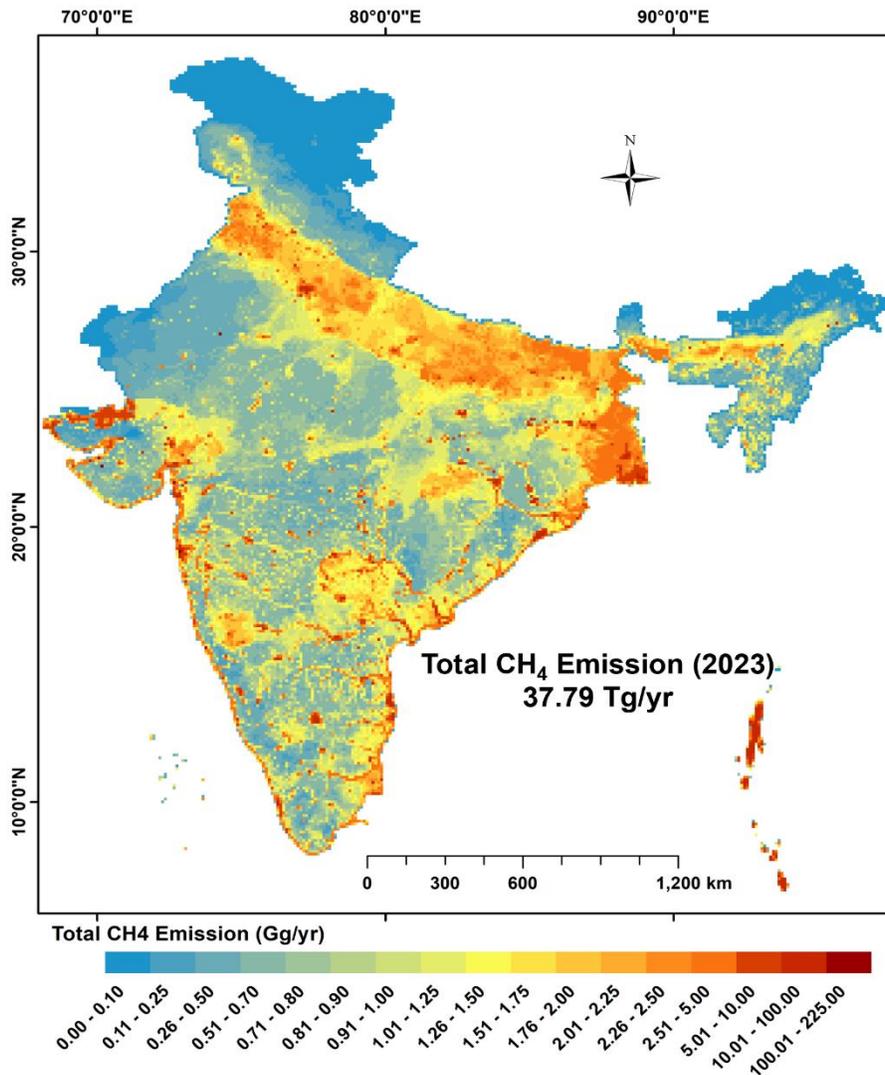


263 Fig 2: Sectoral methane emission from India in 2023 (a) Livestock, (b) Wetland, (c) Rice and  
 264 Sugarcane Crop Field, (d) Waste Management, (e) Fossil Fuel based Activities, (f)  
 265 Remaining sector.

266 In addition to the above sources, there are several sectors contributing to methane  
 267 emission, including organized and unorganized sectors like cooking activities, forest fires,

268 crop residue burning, brick kilns, crematories, and termites. Given the high rural population  
269 density in the Indo-Gangetic region compared to the rest of India, emissions from solid fuel  
270 and biomass-based cooking activities are notably higher, with Uttar Pradesh and Bihar alone  
271 responsible for more than one-fourth of these emissions (MoHA, 2011). Moreover, it is  
272 evident from the spatial maps that cities exhibit lower methane emissions due to lower  
273 livestock density, limited cropland areas, and improved cooking-fuel penetration as  
274 compared to semi-urban and rural regions. Whereas the similar sectors dominate in rural  
275 regions, leading to a shift of the hotspots. In accordance with the shifting cultivation  
276 practices in Northeastern India, forest fires are predominant sources of emissions in that  
277 region. Nearly two-thirds of CH<sub>4</sub> come from those Northeastern states, with Mizoram and  
278 Assam contributing ~ 139 Gg/yr (16%) and 112 Gg/yr (14%), respectively. Methane from crop  
279 residue burning is predominant in Punjab, responsible for nearly one-fourth of emissions  
280 from this sector. Three major agricultural states, Punjab, Madhya Pradesh, and  
281 Maharashtra, collectively emit approximately half of CH<sub>4</sub> emissions. The unorganized brick  
282 kilns sector is particularly found in Indo-Gangetic regions and Central India, where rural  
283 population density is high (MoHA, 2011). Though fly ash and concrete bricks are replacing  
284 mud bricks in urban and semi-urban areas, Northern states like Uttar Pradesh, Bihar, and  
285 Rajasthan still contribute nearly one-third of emissions from this sector. Traditional  
286 cremation practice, is another unorganized source of methane emissions, with the number  
287 of Hindu adherents in a state serving as a key regulatory factor. Uttar Pradesh and  
288 Maharashtra emit 15 Gg/yr of CH<sub>4</sub> out of 30 Gg/yr from the cremation of the deceased.  
289 Natural sources of CH<sub>4</sub>, such as those from termites, have also been accounted for in this  
290 study. Emissions were estimated using forest area as a proxy, with dense forests in Jammu  
291 and Kashmir contributing to higher termite biomass and, consequently, greater CH<sub>4</sub>  
292 emissions. Jammu and Kashmir, Madhya Pradesh, and Odisha jointly contribute one-third  
293 of emissions from the termites. The state-wise top three dominating sectors and districts  
294 listed in Table S5 can be used for mitigation.

295 The grid-wise analysis depicts in Figure 3 that 11,740 (~40%) out of 30,185 grids  
296 account for more than 1 Gg/yr of methane. The per-capita methane footprint of Indians is  
297 found to be 27 kg, and the per square km area CH<sub>4</sub> burden is 11.6 tonnes.



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

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### 3.3 Intercomparison with previous studies

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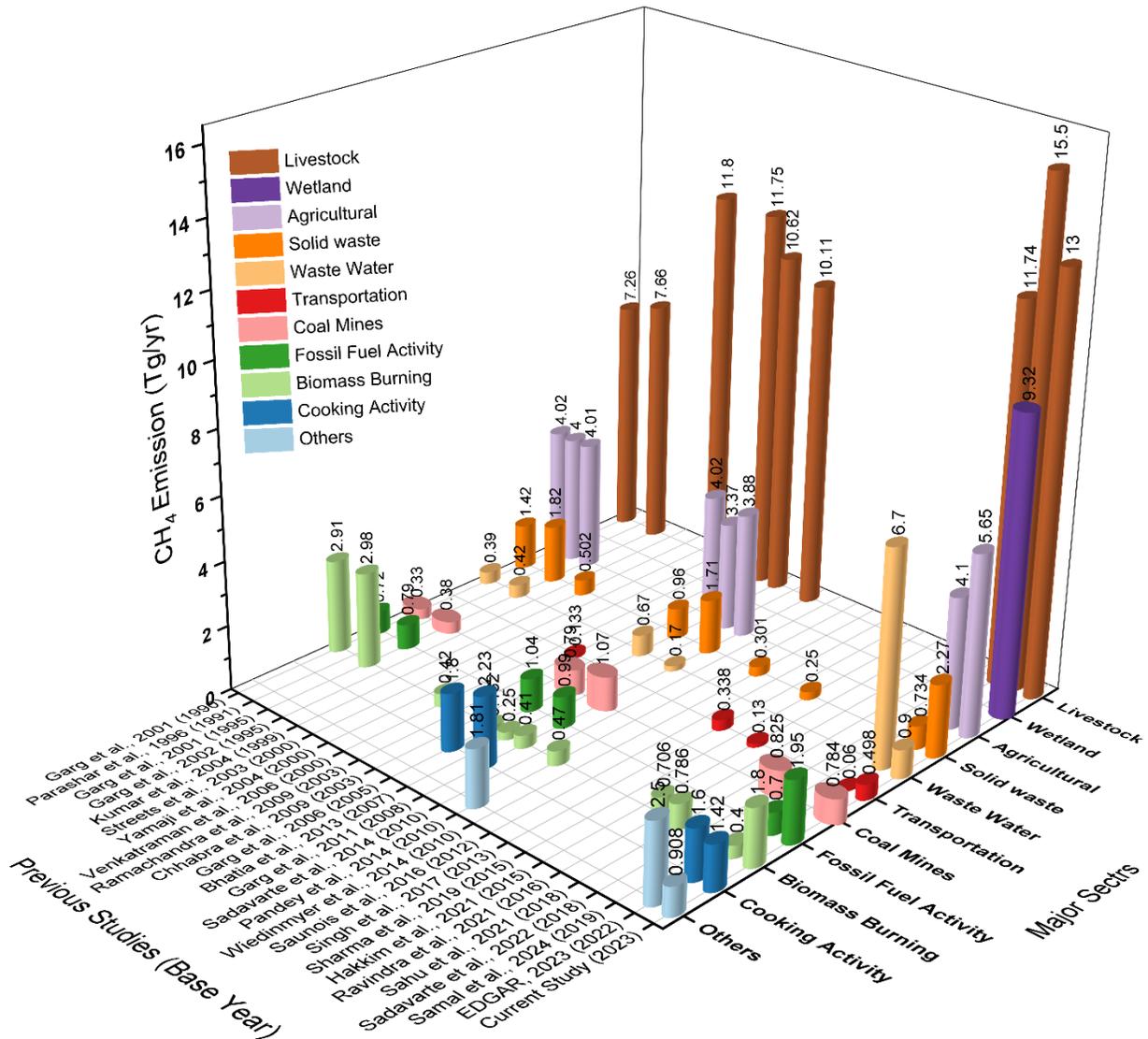
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The intercomparison of CH<sub>4</sub> emissions amongst the current study and previously published papers gives insight into sector-specific contributions and reveals the concurrence and discrepancies in findings over time. Notably, the national-scale comprehensive CH<sub>4</sub> emissions from various types of wetland systems and termites are reported for the first time

305 in this study. The latest estimate of methane emissions from India, as reported by EDGAR,  
306 2023, amounts to 32.3 Tg/yr in 2022. The current study observes a consistent trend of  
307 contribution to total emission across most sectors; however, the estimated emissions from  
308 wastewater are remarkably high, exceeding the current estimate by more than sevenfold.  
309 Unlike the current estimation, EDGAR's lack of regional emission factors has led to some  
310 erratic estimates across various sectors. The current study identifies livestock as the largest  
311 contributor, with methane emissions amounting to 13 Tg/yr. This figure is relatively  
312 consistent with the EDGAR (2023), which reports a slightly higher value of 15.5 Tg/yr.  
313 Previous studies, including those by Samal et al. (2024), Garg et al. (2011) and Garg et al.  
314 (2006), reported emissions of 12.74 Tg/yr, 10.11 Tg/yr, and 10.62 Tg/yr, respectively, for base  
315 years 2019, 2008, and 2005, indicating that livestock has consistently been recognized as a  
316 major source of methane. The variation in estimates is attributable to adopted emission  
317 factors, followed by differences in livestock population, feeding practices, and upgraded  
318 manure management strategies employed in these studies. It is also important to note that,  
319 the current estimate reveals that the agriculture sector comprising livestock and paddy  
320 fields accounts for nearly half of the total CH<sub>4</sub> emission, which debunks the earlier reporting  
321 of the agriculture sector attributed to two-thirds of total emissions from India (Garg et al.,  
322 2001, 2006, 2011, EDGAR, 2023). Agricultural activities, particularly rice and sugarcane  
323 cultivation, contribute 5.65 Tg/yr of methane according to the present study, aligning with  
324 the understanding that India's status as a major rice producer significantly influences global  
325 methane from this sector. However, the EDGAR (2023) inventory reports a lower emission  
326 figure of 4.1 Tg/yr from agriculture, which may have resulted from emission factors  
327 associated with irrigated versus rain-fed rice paddies. Garg et al. (2011) and Garg et al.  
328 (2006) reported lower emissions from agriculture, at 3.88 Tg/yr and 4.02 Tg/yr, respectively.  
329 These discrepancies may reflect changes in agricultural practices, water management  
330 practices, or even climatic conditions that affect methane emissions from paddy fields.

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

334 industrial wastewater. By contrast, the EDGAR (2023) reports significantly higher emissions  
335 from wastewater at 6.7 Tg/yr, yet lower rate from solid waste at 0.73 Tg/yr. This discrepancy  
336 may stem from differences in the scope and methodologies employed in estimating  
337 emissions from urban versus rural waste management practices. Garg et al. (2011, 2006)  
338 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  
339 from wastewater for the years 2008 and 2005, respectively. Although these figures are lower  
340 than those reported in the current study, they suggest a consistent trend in the contribution  
341 of waste management to methane emissions over time. In the fossil fuel sector, including  
342 emissions from coal mining, the current study estimates methane at 1.95 Tg/yr, with 0.78  
343 Tg/yr specifically attributed to coal-mines. In comparison, EDGAR (2023) reports a lower  
344 total of 0.7 Tg/yr from fossil fuel activities, suggesting potential underestimation or  
345 differences in methodologies used to account for fugitive emissions. Garg et al. (2011, 2006)  
346 reported 1.07 Tg/yr and 0.79 Tg/yr of methane emissions from fossil fuels, in the respective  
347 studies, which are lower figures but still indicate a recognized contribution from this sector  
348 over time. The current study estimates methane from biomass burning at 1.8 Tg/yr while  
349 emissions from cooking activities contribute 1.42 Tg/yr. These figures align somewhat with  
350 previous estimates, such as the 1.6 Tg/yr for biomass burning reported in EDGAR (2023).  
351 However, estimates for cooking activities vary significantly across studies. For instance,  
352 Garg et al. (2011) reported 2.23 Tg/yr, and Pandey et al. (2014) estimated 2.31 Tg/yr, both of  
353 which are higher than the current study's figure. These variations could reflect differences  
354 in the types of fuels considered, the efficiency of stoves, or regional cooking practices. The  
355 intercomparison between the current and previous studies is illustrated in Figure 4.



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

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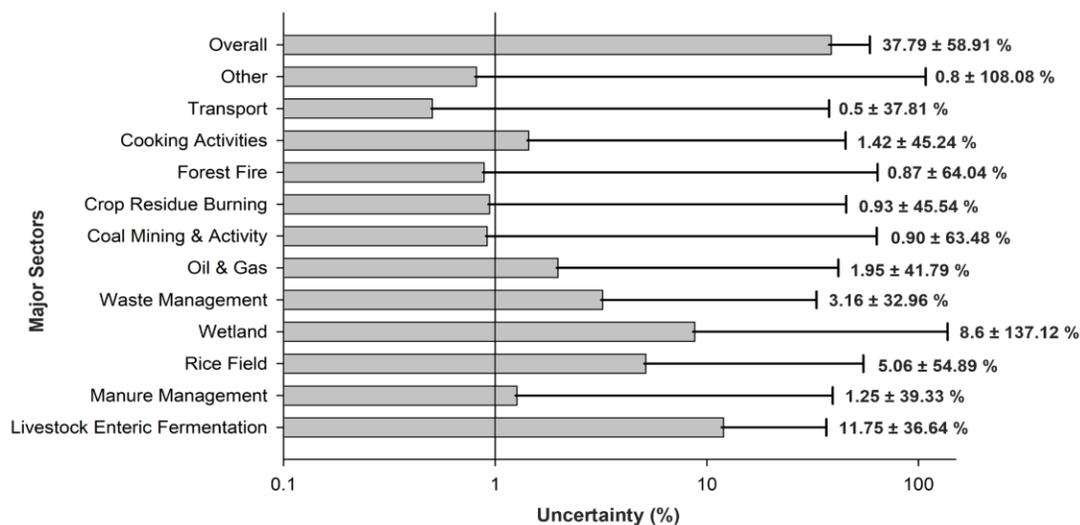
In the current study, natural sources such as wetlands contribute 8.6 Tg/yr of methane (the second most dominant contributor), a notable figure that has not been explicitly detailed in many previous studies. The inclusion of wetlands as a significant source in this study underscores a growing recognition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

365 sources of methane, the exact magnitude varies considerably across studies due to  
366 differences in methodologies, emission factors used, and the scope of sectors considered.  
367 Traditionally, livestock, agriculture, and solid waste have been acknowledged as major  
368 contributors. However, the current study emphasizes the higher contributions from natural  
369 sources like wetlands and man-made solid waste, reflecting an evolving understanding of  
370 methane emissions in India. Moreover, earlier atmospheric methane inversion estimates by  
371 Ganeshan et al (2017), Miller et al (2019), Chandra et al (2021) and Janardan et al (2024)  
372 estimated 22 Tg/yr (2015), 35 Tg/yr (2015), 49 Tg/yr (2016), 29.24 Tg/yr (2020), respectively  
373 over India. The direct quantitative comparison with this 2023 bottom-up inventory is  
374 challenging due to varying base year-specific activity data and emission trends.  
375 Nevertheless, our national total of 37.79 Tg/yr falls comfortably within this observed range  
376 of inversion estimates, providing robustness to the inventory's magnitude.

### 377 **3.4 Uncertainty Estimation**

378 Although the current study on methane emissions in India is extensive, it  
379 acknowledges inherent limitations in its estimations. The reliance on secondary activity  
380 data and emission factors and the lack of sufficient details introduces a degree of  
381 uncertainty. Despite these limitations, the study addresses crucial aspects of filling the data  
382 gap and providing support to climate modeling and will be instrumental in identifying  
383 methane hotspots across the country. It will also enhance the quantification of the roles  
384 played by various natural and anthropogenic sources in the country, thereby assisting  
385 policymakers in implementing advanced technological mitigation strategies to reduce  
386 methane emissions. The uncertainty of all the individual sectors lies in the range of  $\pm 32$ -  
387 161% where the natural sources like wetlands and termites have higher uncertainty levels  
388 of  $\pm 137\%$  and  $\pm 161\%$  respectively. The uncertainty estimated from waste management is  
389 restricted to  $\pm 33\%$ . The overall uncertainty of the current CH<sub>4</sub> emission inventory is found to  
390 be  $\pm 59\%$ . The sector-specific uncertainty level is illustrated in Figure 5. The comparatively  
391 higher uncertainty associated with certain source categories, particularly wetlands and  
392 termites, primarily reflects deficiencies in high-resolution activity data and the limited

393 availability of region-specific and country-wise emission factors. These natural sources are  
394 inherently difficult to constrain due to strong spatial and seasonal variability and their  
395 dependence on environmental drivers. Although sectoral uncertainties may affect the  
396 magnitude of emissions at localized scales, they do not compromise the integrity of the  
397 broader spatial patterns. Most of the previous studies haven't reported the sector-wise  
398 uncertainties for India specifically and global studies like Saunio et al. (2025) have reported  
399 the uncertainty of ~45% for Southeast Asia as a whole. This is the mean uncertainty  
400 calculated for all other nations in Southeast Asia, including India, where the uncertainty  
401 associated with large country like India is unclear. Solazzo et al. (2021) presented the  
402 sectoral uncertainties of CH<sub>4</sub> in the EDGAR estimation for India. The reported uncertainties  
403 in the Energy: fuel consumption sector were found to be 223%, followed by Oil & Gas (139%),  
404 Waste (107%), Solid fuels (57%), Industrial processes and product use (42%), and  
405 Agriculture (42%). However, the uncertainty reported here is improved with the use of  
406 regional activity data, diverse proxy data and regional scale sectoral emission factors. The  
407 uncertainty shoots up with the inclusion of natural sources like emissions from Wetlands  
408 (Inland wetland, Coastal wetland & Mangroves) and Termites. It is observed that uncertainty  
409 associate with small sectors like coal mining, forest fire is high as compared to major  
410 traditional sectors like Livestock and paddy field. Besides these sectors, the overall  
411 anthropogenic emission uncertainty is found to be ~44%, improving the reliability of  
412 developed present inventory and robustness of the emission dataset. The higher uncertainty  
413 for various sources, including natural sources, is due to the paucity of updated  
414 technological emission factors. With higher emissions and higher uncertainty of the wetland  
415 sector, it alone drives the uncertainty upward.



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

#### 418 4. Conclusion

419 The present study not only addresses the reporting of the most recent gridded  
 420 methane dataset over India by synthesizing country-specific 25 distinct major and minor  
 421 natural and anthropogenic sources but also fills the gap in the country's methane budget.  
 422 The total methane emissions for the most recent base year, i.e., 2023, are found to be 37.79  
 423 Tg/yr, with approximately 75% attributed to anthropogenic activities. Methane data will be  
 424 a crucial input not only for climate modeling but also for understanding India's contribution  
 425 to the global methane budget. The study reports many sub-sectors of wetlands and  
 426 termites, which are the first-of-its-kind to strengthen the understanding of methane  
 427 emissions in India. This newly developed state-of-the-art, high-resolution gridded methane  
 428 dataset would be valuable input for climate models to optimize simulation.

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#### 432 Conflicts of interest

433 The authors declare that they have no known competing financial interests or personal  
434 relationships that could have appeared to influence the work reported in this paper.

435 **Data availability statements**

436 The data supporting this article has been included as part of the Supplementary Information.  
437 The emission dataset can be accessed through the open-access data repository Zenodo.  
438 Methane Emission Data [Dataset]. <https://doi.org/10.5281/zenodo.14089138>. (Sahu, S. K.,  
439 2024).

440 **Author contributions:**

441 AM wrote the whole paper and analyzed and plotted the scientific data for necessary  
442 discussion. PM and PS helped in the analysis and provided useful insight. GB and RJ  
443 reviewed the article and suggested a justified conclusion, and SKS conceived the present  
444 idea, analyzed the data and reviewed the manuscript.

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