

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

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13 **Abstract**

14 Methane (CH₄) 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 CH₄ emission by including 25 distinct
21 anthropogenic and natural sources in India for 2023 by adopting the IPCC bottom-up
22 approach. The estimated CH₄ 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 CH₄ 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

35 1. Introduction

36 Methane (CH₄) is the second most abundant and potent greenhouse gas (GHG) in the
37 atmosphere, after Carbon Dioxide (CO₂) (European Commission, 2023). Its ability to trap
38 heat by absorbing outgoing thermal infrared radiation is 28 times more than CO₂ resulting in
39 16-25% of atmospheric warming to date (Rosentreter et al., 2021). The surface dry-air mole
40 fraction of atmospheric CH₄ has escalated to 1931 ppb, nearly 2.6 times the level recorded
41 in the preindustrial era of 1750 (NOAA, 2024). The significant rise in CH₄ concentrations
42 necessitates urgent mitigation of methane emissions, given its potential to induce near-
43 term climatic changes and its involvement in the formation of tropospheric ozone.

44 The global CH₄ emissions in 2017 were estimated through the bottom-up approach
45 amounted to be ~747 (602–896) Tg/yr, primarily contributed by anthropogenic sources
46 (Saunois et al., 2020). China is responsible for the highest emissions with more than 20% of
47 the global anthropogenic CH₄, followed by South Asia (13%), Southeast Asia (8%), and the
48 United States of America (USA) (7%) (Saunois et al., 2020). The anthropogenic emissions are
49 attributed to various sources like livestock, agriculture, solid waste, wastewater
50 management, fossil fuel production, biomass burning, etc. Given the extensive domestic
51 and agricultural practices such as livestock and vegetative culture, South Asian regions are
52 a global hotspot of CH₄ emissions (Saunois et al., 2020). Given the diversity of methane
53 sources across the world, the real challenge lies in identifying the country-specific prevailing
54 and predominant sources that may have a disproportionate contribution to the national
55 total emissions. Understanding regional sources in developing nations like India is
56 paramount, where the spatial diversity of sources is much more complex, to identify and
57 quantify methane emissions comprehensively. As per India's third Biennial Update Report
58 to the United Nations Framework Convention on Climate Change (UNFCCC), Indian
59 agriculture sectors contributed nearly 75% of national total methane emissions in 2016
60 (excluding Land Use, Land Use Change, and Forestry) (MoEFCC, 2021). Owing to this report,
61 the Government of India (GoI) has implemented numerous policies like the National
62 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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄ 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, Saunio
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 CH₄ emissions in India. Parasher et al. (1996) reported 4 Tg/yr of CH₄ 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 CH₄ emission. The CH₄ 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 CH₄. Similarly, activities based on biomass and fossil fuels contribute

92 substantially to national CH₄ 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 (CH₄) 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: -

$$132 \quad E = \sum_a \sum_b F_{a,b} [\sum_c E_{f_{a,b,c}} A_{a,b,c}] \quad (1)$$

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.

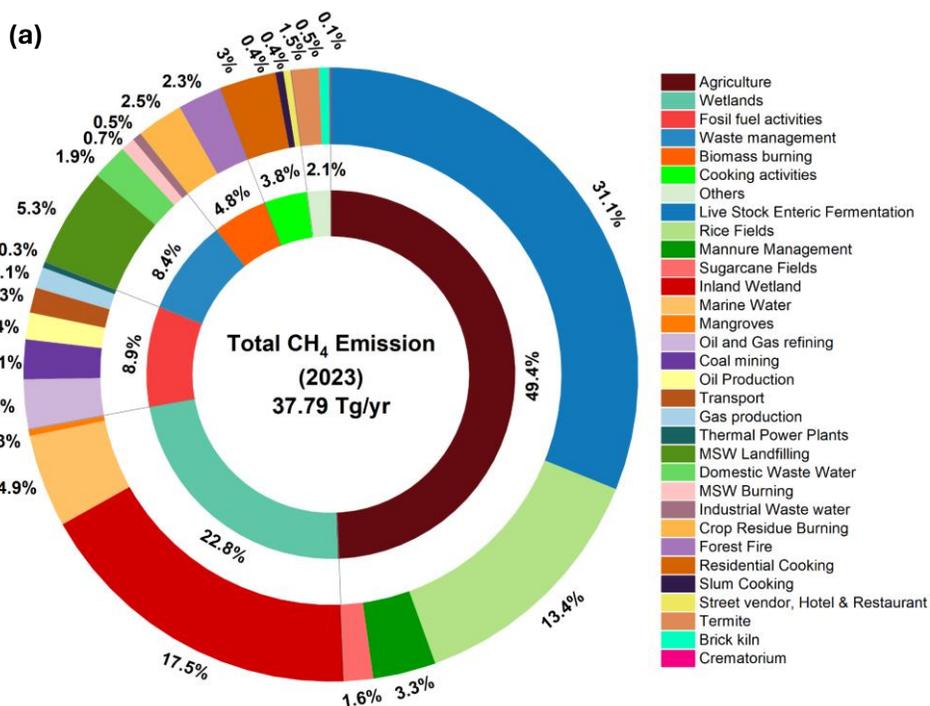
138 **3. Results and discussion**

139 **3.1 Sectoral contribution to total CH₄ 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

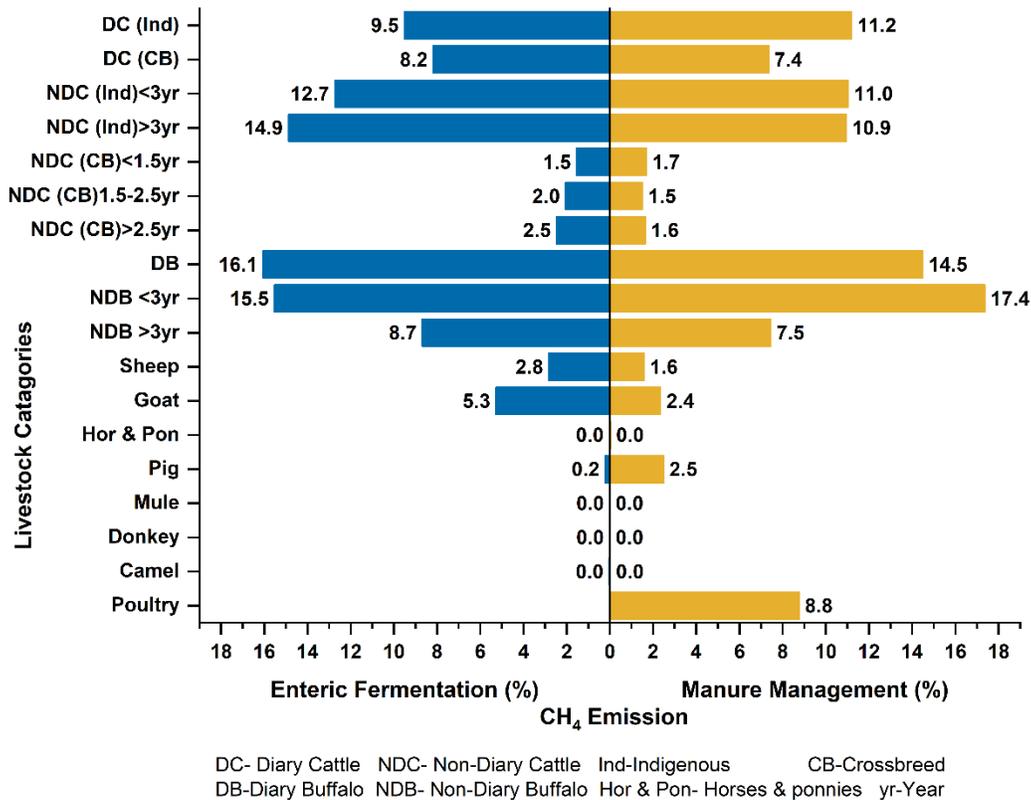
147 emissions from fossil fuel-based activities, which accounted for approximately 9% (3.35
 148 Tg/yr), waste management (~8%), biomass burning (~5%), cooking activities (~4%), and
 149 other miscellaneous sources comprising about ~2% of the total emissions, as illustrated in
 150 Figure 1 (a).

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

(b)



163

164 Fig 1: (a) Sectoral Contribution of CH₄ emission (% total), (b) Livestock (% of sector)
 165 in 2023

166 Wetlands have emerged as the second largest source of CH₄ emissions in India,
 167 where the inland wetlands contribute the highest (~17%) followed by rice fields (~13%). The
 168 present attempt examines the comprehensive coastal CH₄ budget, revealing that the marine
 169 wetlands in coastal areas emit roughly 1.85 Tg/yr. Additionally, the sensitive mangrove
 170 ecosystems release 0.84 Tg/yr into the atmosphere. The emission analysis also included
 171 data on rice and sugarcane cropping areas, as well as irrigation statistics, retrieved from the
 172 Ministry of Agriculture and Farmers’ Welfare. The findings indicate that flooded agricultural
 173 lands contribute more significantly to methane emissions compared to single-irrigation or
 174 drought-prone regions, with rice fields alone responsible for 5.65 Tg/yr of CH₄. In addition to
 175 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 CH₄. 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 CH₄ in 2023.

185 **3.2 Spatial variability in CH₄**

186 The spatially resolved estimated CH₄ 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), CH₄ 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 CH₄
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 CH₄ 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 CH₄ 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 CH₄ 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 CH₄
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 CH₄ 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 CH₄ 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 CH₄ 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).

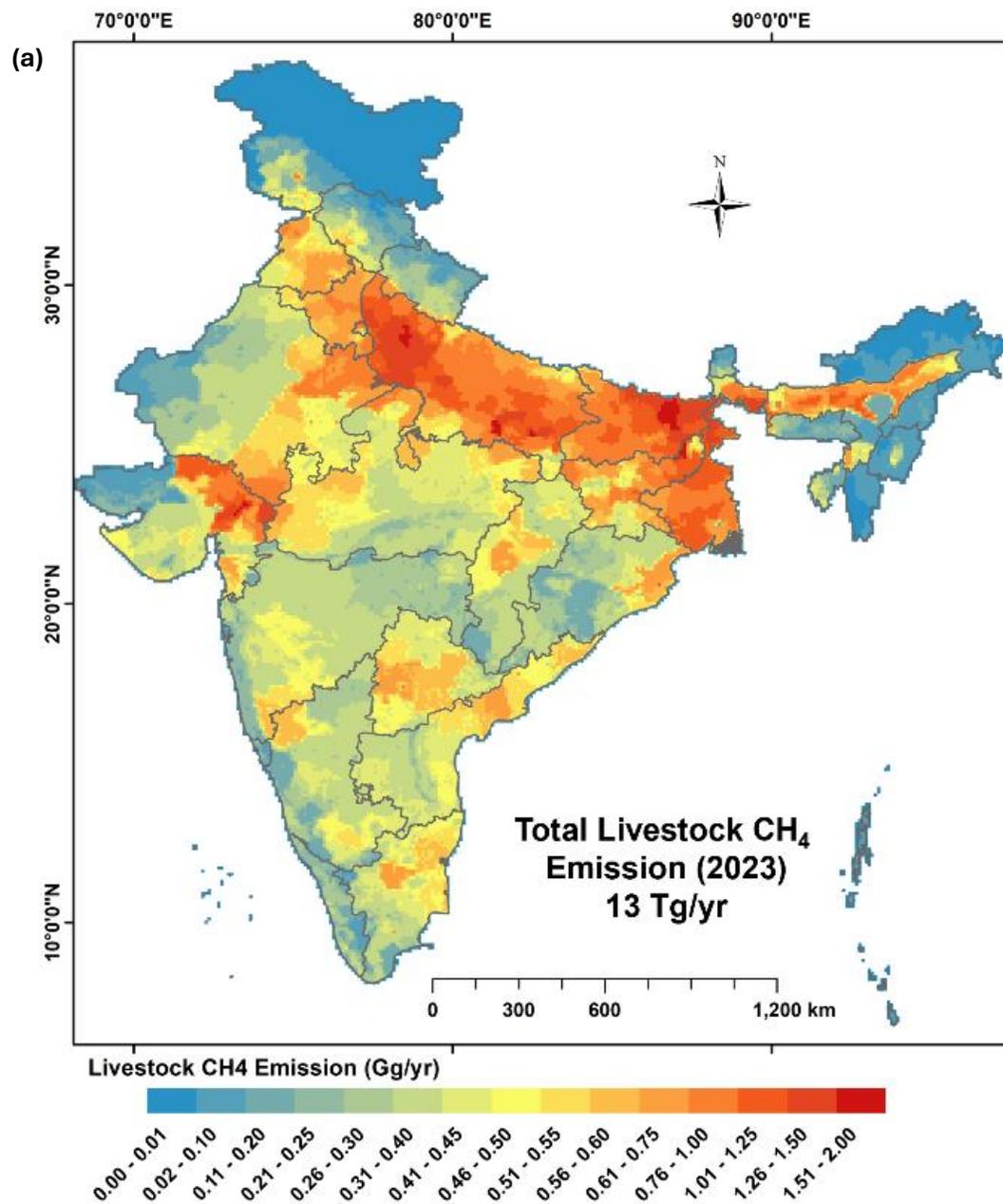
222 The spatial distribution of CH₄ from cropland exhibits a pattern closely aligned with
223 that of inland wetlands, particularly in regions where intensive cropping practices are
224 observed near freshwater bodies and experiencing monsoons. Indo-Gangetic basin,
225 Brahmaputra basin, East Coastal, 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 CH₄ 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

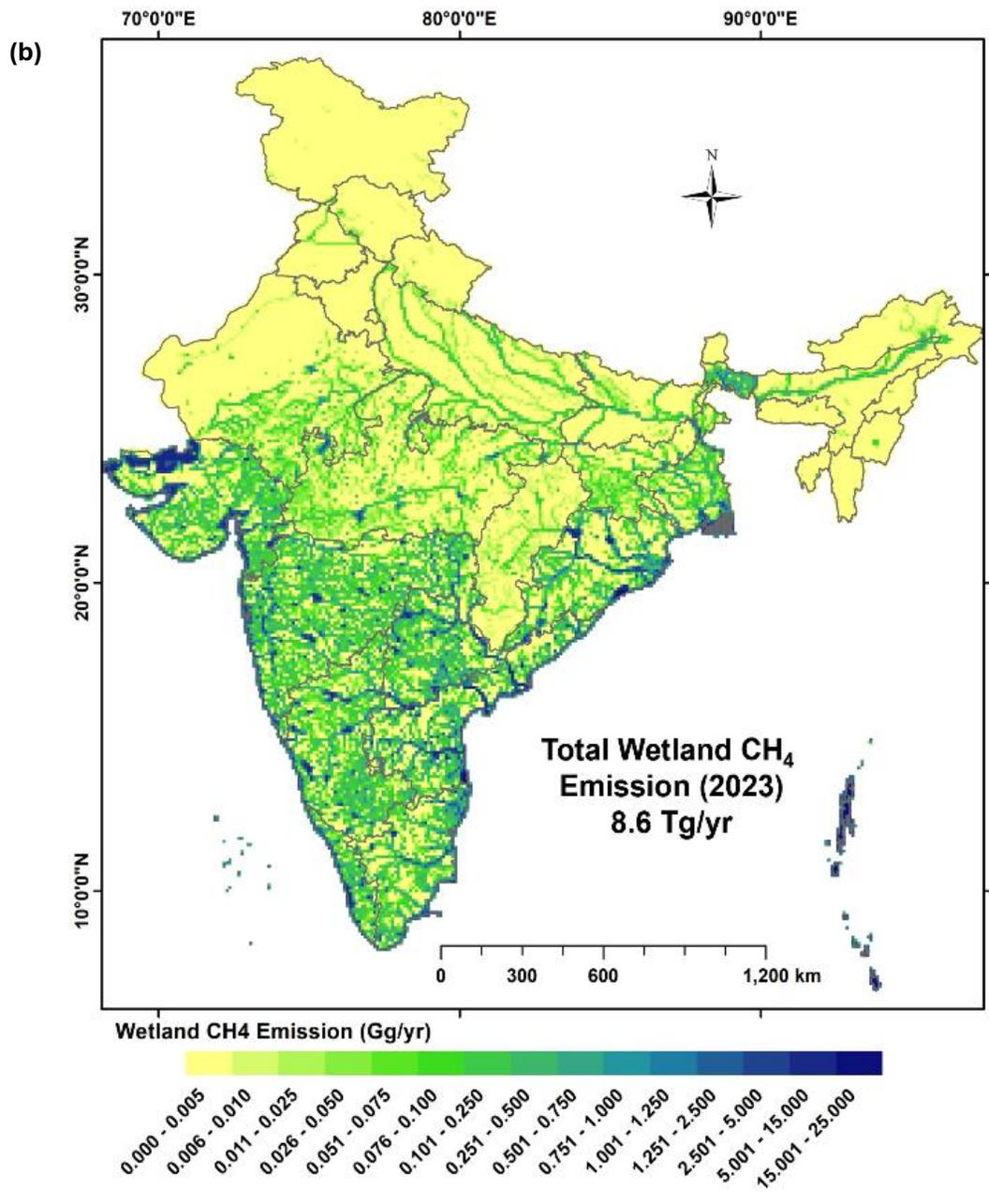
232 emissions from crop fields originate from the top 90 districts out of which Nalgonda
233 (Telangana), Paschim Medinipur (West Bengal) and Karimnagar (Telangana) are the leading
234 emitters.

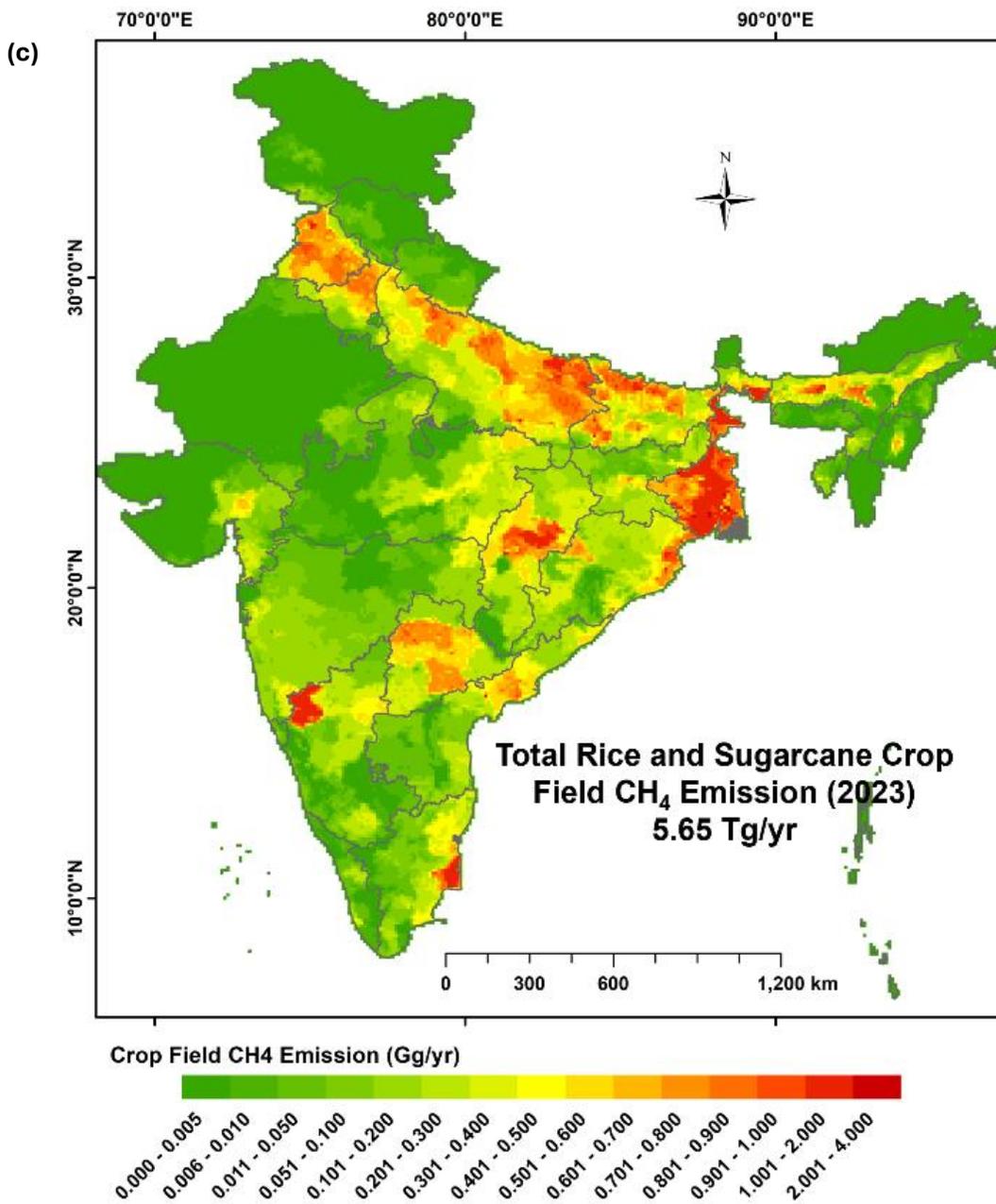
235 Waste management poses a significant challenge in developing India, where the
236 burden of waste and its associated pollution has adversely affected urban living conditions.
237 It is evident from Figure 2(d) that the Indo-Gangetic Basin states are more susceptible to high
238 emissions than rest India. In solid waste management like burning and landfilling, Uttar
239 Pradesh contributes ~ 303 Gg/yr (13%), followed by Maharashtra ~ 229 Gg/yr (10%) and Bihar
240 ~ 200 Gg/yr (9%). Similarly, in the wastewater management sector, Maharashtra is the
241 largest contributor, responsible for approximately 202 Gg/yr (23%), with Gujarat, Uttar
242 Pradesh, and Tamil Nadu contributing 97 Gg/yr (11%), 79 Gg/yr (9%), and 76 Gg/yr (8%),
243 respectively. Collectively, Maharashtra accounts for the highest proportion of methane
244 emissions from the waste management sector, with 14%, followed by Uttar Pradesh and
245 Gujarat, with 12% and 7%, respectively. Further analysis indicates that more than half of the
246 CH₄ emissions from the combined waste management sector originate from the top 100
247 districts across the country.

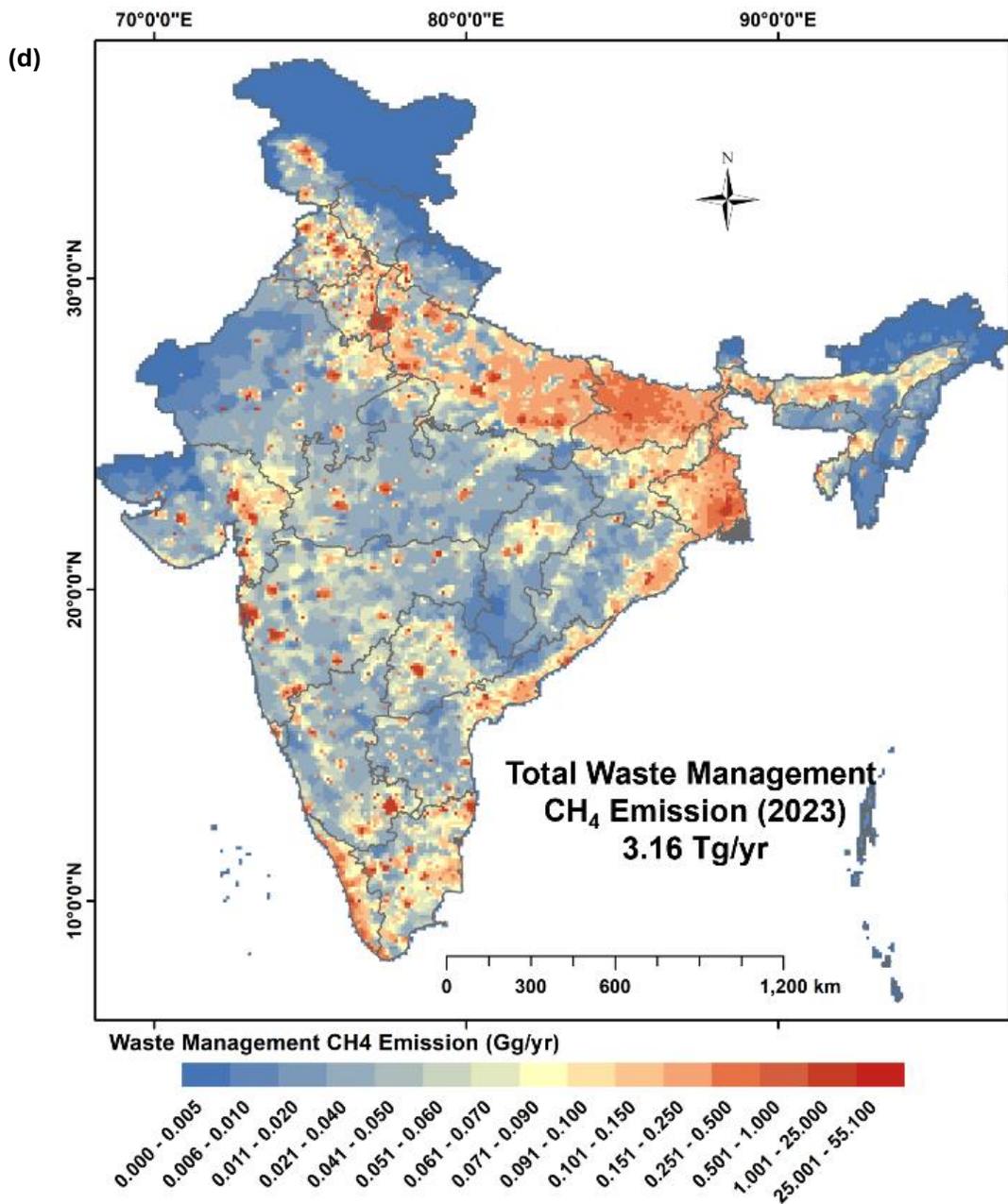
248 Methane is also primarily attributed to traditional fossil fuel consumption for energy,
249 which includes coal mining, TPP, oil & gas extraction, refineries, and transportation activity.
250 The states in the Central and Eastern India region, like Chhattisgarh, Odisha, Jharkhand, and
251 Madhya Pradesh collectively emit two-thirds of CH₄ emissions due to intense coal mining
252 activities and substantial coal reserves within these regions. Further, the presence of high-
253 capacity oil refineries in states like Gujarat, Maharashtra, and Assam over Western, and
254 North-Eastern regions is jointly responsible for half of the emissions from the Oil & Gas
255 sector. Though a very small amount is emitted from TPP, Maharashtra, Madhya Pradesh,
256 Chhattisgarh, Uttar Pradesh and Odisha contribute nearly 50% of emissions due to the
257 presence of supercritical and ultra-supercritical power units. Similarly, significant
258 transport-related emissions dominated over industrialized and populated states like
259 Maharashtra, Rajasthan, Uttar Pradesh, Gujarat and Tamil Nadu, resulting in more than one-

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

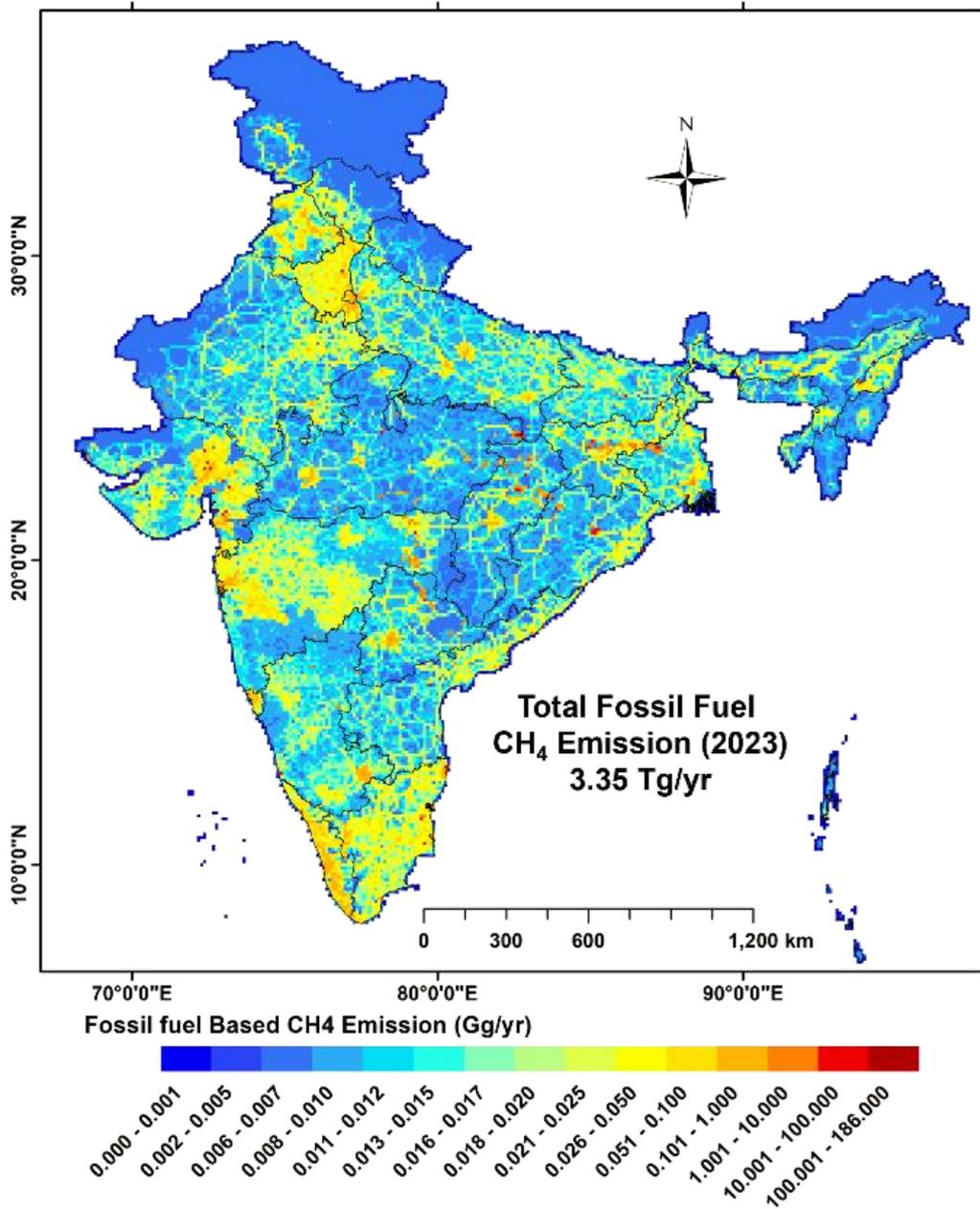


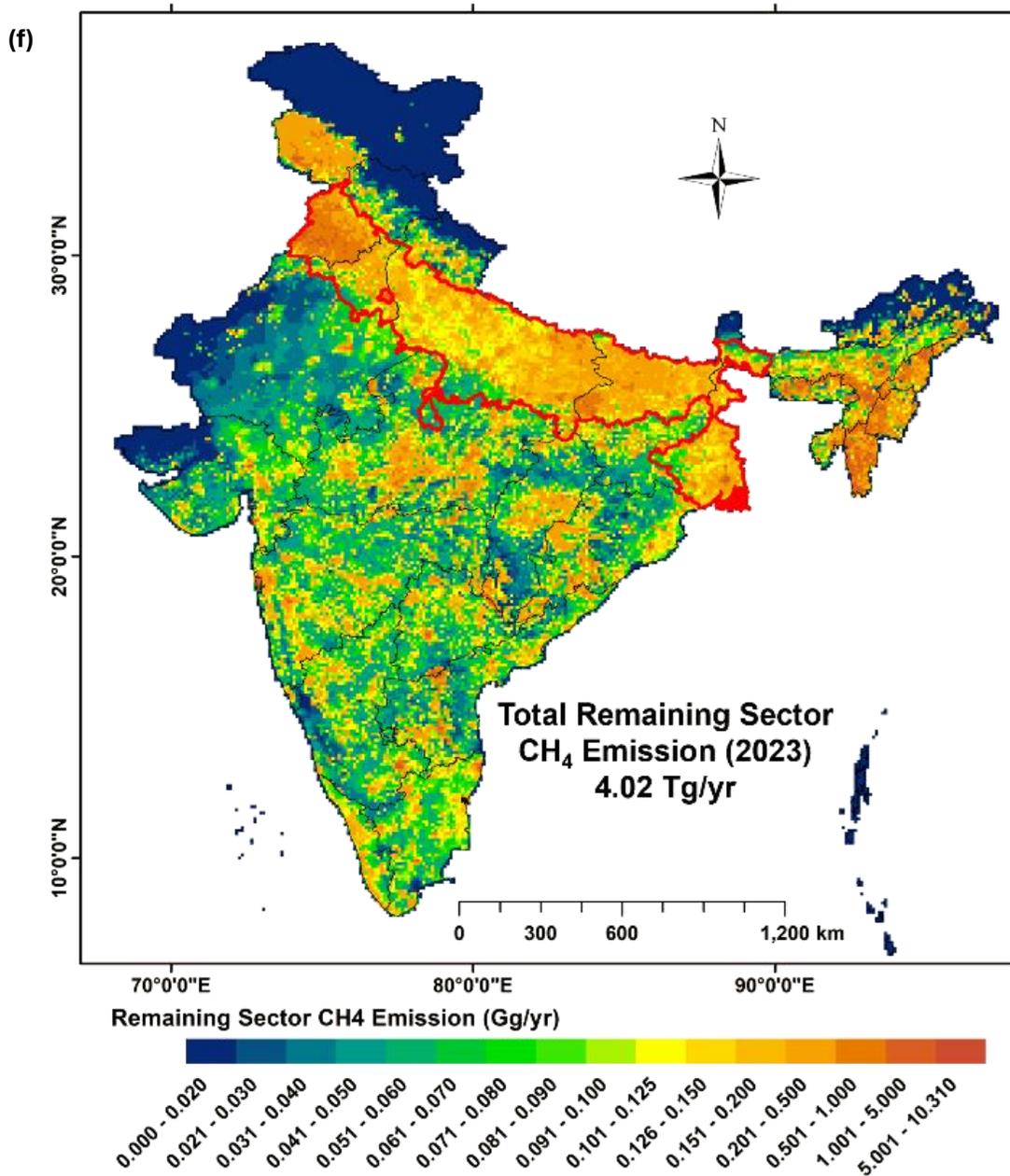






(e)



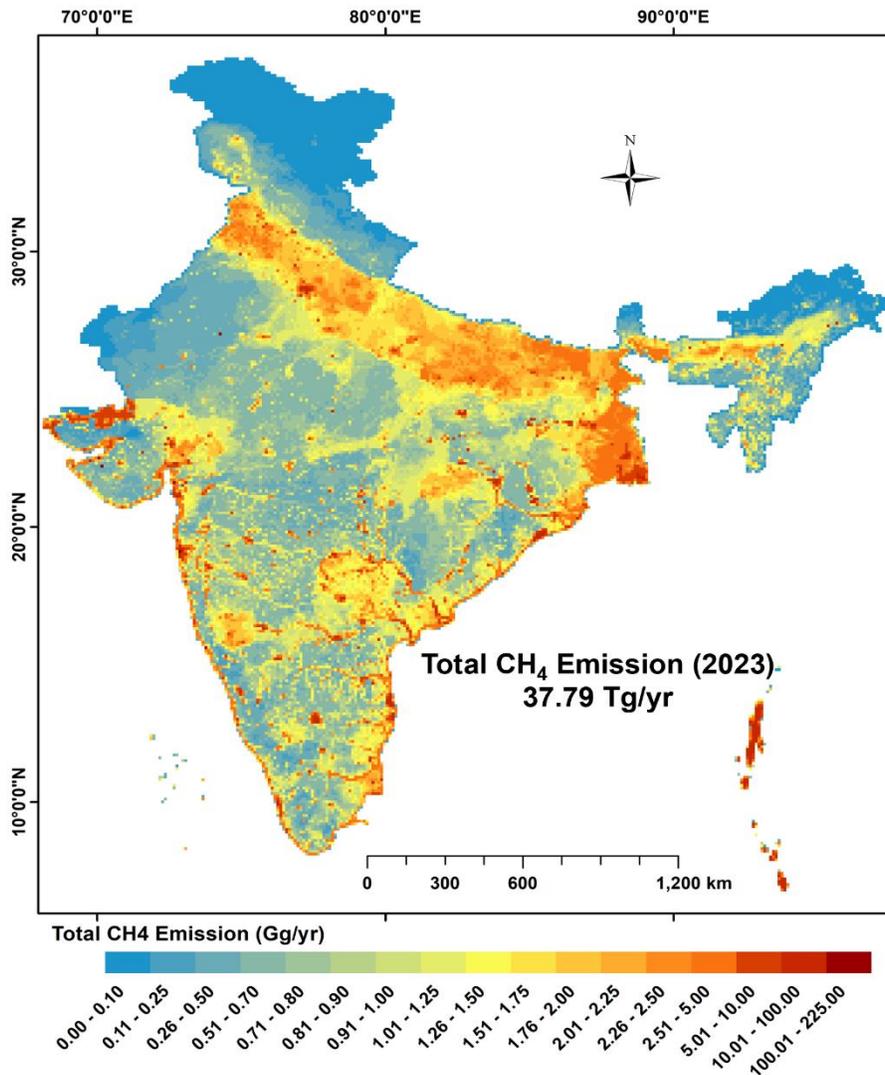


264 Fig 2: Sectoral methane emission from India in 2023 (a) Livestock, (b) Wetland, (c) Rice and
 265 Sugarcane Crop Field, (d) Waste Management, (e) Fossil Fuel based Activities, (f)
 266 Remaining sector.

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,

269 crop residue burning, brick kilns, crematories, and termites. Given the high rural population
270 density in the Indo-Gangetic region compared to the rest of India, emissions from solid fuel
271 and biomass-based cooking activities are notably higher, with Uttar Pradesh and Bihar alone
272 responsible for more than one-fourth of these emissions (MoHA, 2011). Moreover, it is
273 evident from the spatial maps that cities exhibit lower methane emissions due to lower
274 livestock density, limited cropland areas, and improved cooking-fuel penetration as
275 compared to semi-urban and rural regions. Whereas the similar sectors dominate in rural
276 regions, leading to a shift of the hotspots. In accordance with the shifting cultivation
277 practices in Northeastern India, forest fires are predominant sources of emissions in that
278 region. Nearly two-thirds of CH₄ come from those Northeastern states, with Mizoram and
279 Assam contributing ~ 139 Gg/yr (16%) and 112 Gg/yr (14%), respectively. Methane from crop
280 residue burning is predominant in Punjab, responsible for nearly one-fourth of emissions
281 from this sector. Three major agricultural states, Punjab, Madhya Pradesh, and
282 Maharashtra, collectively emit approximately half of CH₄ emissions. The unorganized brick
283 kilns sector is particularly found in Indo-Gangetic regions and Central India, where rural
284 population density is high (MoHA, 2011). Though fly ash and concrete bricks are replacing
285 mud bricks in urban and semi-urban areas, Northern states like Uttar Pradesh, Bihar, and
286 Rajasthan still contribute nearly one-third of emissions from this sector. Traditional
287 cremation practice, is another unorganized source of methane emissions, with the number
288 of Hindu adherents in a state serving as a key regulatory factor. Uttar Pradesh and
289 Maharashtra emit 15 Gg/yr of CH₄ out of 30 Gg/yr from the cremation of the deceased.
290 Natural sources of CH₄, such as those from termites, have also been accounted for in this
291 study. Emissions were estimated using forest area as a proxy, with dense forests in Jammu
292 and Kashmir contributing to higher termite biomass and, consequently, greater CH₄
293 emissions. Jammu and Kashmir, Madhya Pradesh, and Odisha jointly contribute one-third
294 of emissions from the termites. The state-wise top three dominating sectors and districts
295 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 CH₄ burden is 11.6 tonnes.



299

300

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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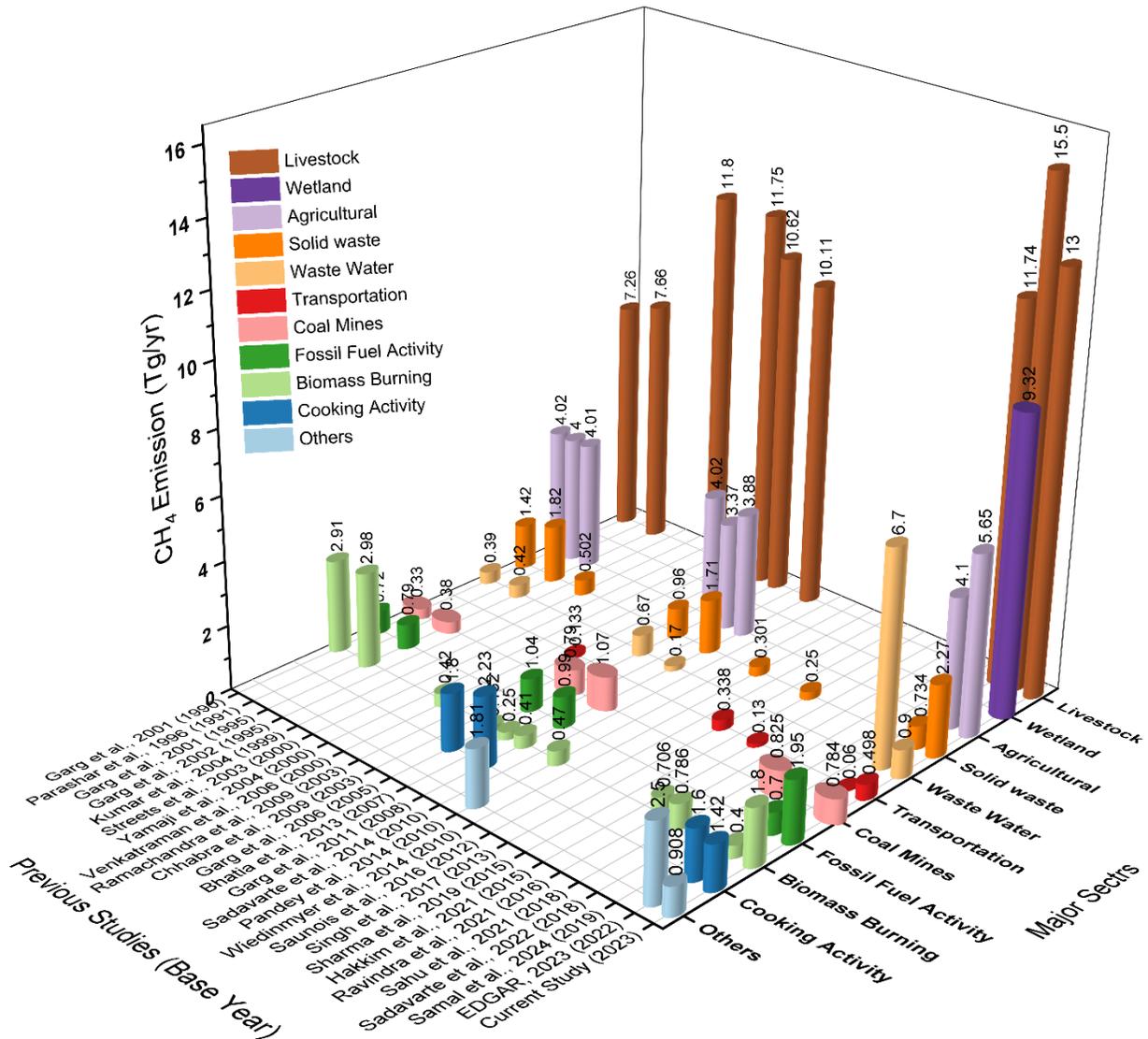
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The intercomparison of CH₄ emissions amongst the current study and previously published papers gives insight into sector-specific contributions and reveals the concurrence and discrepancies in findings over time. Notably, the national-scale comprehensive CH₄ 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 CH₄ 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.



358

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

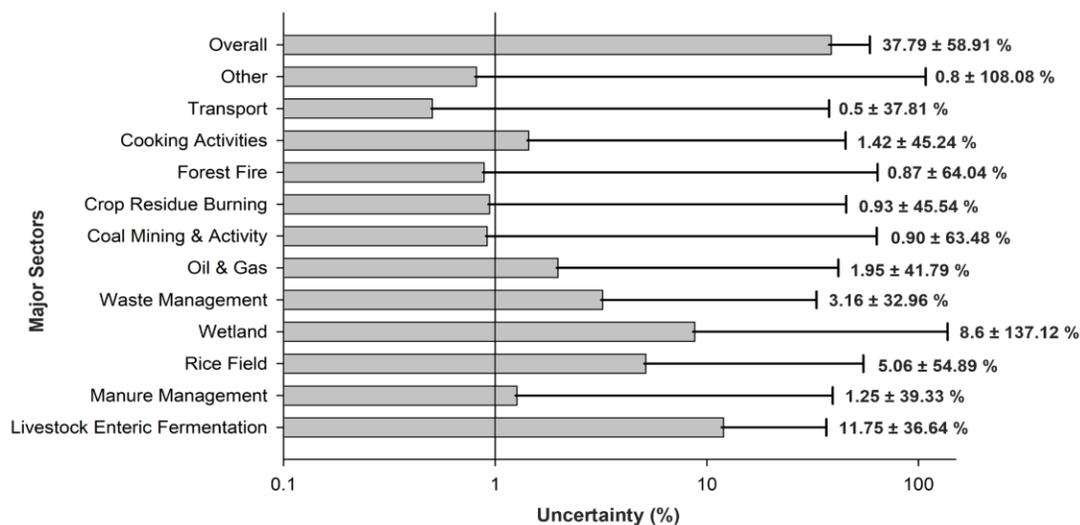
360 In the current study, natural sources such as wetlands contribute 8.6 Tg/yr of
 361 methane (the second most dominant contributor), a notable figure that has not been
 362 explicitly detailed in many previous studies. The inclusion of wetlands as a significant
 363 source in this study underscores 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 $\pm 137\%$ and $\pm 161\%$ respectively. The uncertainty estimated from waste management is
390 restricted to $\pm 33\%$. The overall uncertainty of the current CH₄ emission inventory is found to
391 be $\pm 59\%$. 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
395 inherently difficult to constrain due to strong spatial and seasonal variability and their
396 dependence on environmental drivers. Although sectoral uncertainties may affect the
397 magnitude of emissions at localized scales, they do not compromise the integrity of the
398 broader spatial patterns. Most of the previous studies haven't reported the sector-wise
399 uncertainties for India specifically and global studies like Saunio et al. (2025) have reported
400 the uncertainty of ~45% for Southeast Asia as a whole. This is the mean uncertainty
401 calculated for all other nations in Southeast Asia, including India, where the uncertainty
402 associated with large country like India is unclear. Solazzo et al. (2021) presented the
403 sectoral uncertainties of CH₄ in the EDGAR estimation for India. The reported uncertainties
404 in the Energy: fuel consumption sector were found to be 223%, followed by Oil & Gas (139%),
405 Waste (107%), Solid fuels (57%), Industrial processes and product use (42%), and
406 Agriculture (42%). However, the uncertainty reported here is improved with the use of
407 regional activity data, diverse proxy data and regional scale sectoral emission factors. The
408 uncertainty shoots up with the inclusion of natural sources like emissions from Wetlands
409 (Inland wetland, Coastal wetland & Mangroves) and Termites. It is observed that uncertainty
410 associate with small sectors like coal mining, forest fire is high as compared to major
411 traditional sectors like Livestock and paddy field. Besides these sectors, the overall
412 anthropogenic emission uncertainty is found to be ~44%, improving the reliability of
413 developed present inventory and robustness of the emission dataset. The higher uncertainty
414 for various sources, including natural sources, is due to the paucity of updated
415 technological emission factors. With higher emissions and higher uncertainty of the wetland
416 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.

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433 **Conflicts of interest**

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

446 **References**

- 447 Chandra, N., Patra, P. K., Bisht, J. S. H., Ito, A., Umezawa, T., Saigusa, N., Morimoto, S., Aoki,
448 S., Janssens-Maenhout, G., Fujita, R., Takigawa, M., Watanabe, S., Saitoh, N., And
449 Canadell, J. G.: Emissions from the Oil and Gas Sectors, Coal Mining and Ruminant
450 Farming Drive Methane Growth over the Past Three Decades, Journal of the
451 Meteorological Society of Japan. Ser. II, 99, 309–337,
452 <https://doi.org/10.2151/jmsj.2021-015>, 2021.
- 453 EDGAR - The Emissions Database for Global Atmospheric Research:
454 https://edgar.jrc.ec.europa.eu/report_2023.
- 455 European Commission: Methane emissions, [https://energy.ec.europa.eu/topics/carbon-](https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en)
456 [management-and-fossil-fuels/methane-emissions_en](https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/methane-emissions_en).
- 457 Ganesan, A. L., Rigby, M., Lunt, M. F., Parker, R. J., Boesch, H., Goulding, N., Umezawa, T.,
458 Zahn, A., Chatterjee, A., Prinn, R. G., Tiwari, Y. K., Marcel, and Krummel, P. B.:
459 Atmospheric observations show accurate reporting and little growth in India's
460 methane emissions, Nature Communications, 8, [https://doi.org/10.1038/s41467-](https://doi.org/10.1038/s41467-017-00994-7)
461 [017-00994-7](https://doi.org/10.1038/s41467-017-00994-7), 2017.
- 462 Garg, A., Bhattacharya, S., Shukla, P. R., and Dadhwal, V. K.: Regional and sectoral
463 assessment of greenhouse gas emissions in India, Atmospheric Environment, 35,
464 2679–2695, [https://doi.org/10.1016/s1352-2310\(00\)00414-3](https://doi.org/10.1016/s1352-2310(00)00414-3), 2001.
- 465 Garg, A., Shukla, P. R., and Kapshe, M.: The sectoral trends of multigas emissions inventory
466 of India, Atmospheric Environment, 40, 4608–4620,
467 <https://doi.org/10.1016/j.atmosenv.2006.03.045>, 2006.
- 468 Garg, A., Kankal, B., and Shukla, P. R.: Methane emissions in India: Sub-regional and
469 sectoral trends, Atmospheric Environment, 45, 4922–4929,
470 <https://doi.org/10.1016/j.atmosenv.2011.06.004>, 2011.
- 471 Janardanan, R., Maksyutov, S., Wang, F., Nayagam, L., Sahu, S. K., Mangaraj, P., Saunio,
472 M., Lan, X., and Matsunaga, T.: Country-level methane emissions and their sectoral

473 trends during 2009–2020 estimated by high-resolution inversion of GOSAT and surface
474 observations, *Environmental Research Letters*, 19, 034007–034007,
475 <https://doi.org/10.1088/1748-9326/ad2436>, 2024.

476 Mangaraj, P., Sahu, S. K., Beig, G., and Yadav, R.: A comprehensive high-resolution gridded
477 emission inventory of anthropogenic sources of air pollutants in Indian megacity
478 Kolkata, *SN Applied Sciences*, 4, <https://doi.org/10.1007/s42452-022-05001-3>,
479 2022a.

480 Mangaraj, P., Sahu, S. K., Beig, G., and Samal, B.: Development and assessment of inventory
481 of air pollutants that deteriorate the air quality in Indian megacity Bengaluru, *Journal*
482 *of Cleaner Production*, 360, 132209, <https://doi.org/10.1016/j.jclepro.2022.132209>,
483 2022b.

484 Mangaraj, P., Sahu, S. K., and Beig, G.: Development of emission inventory for air quality
485 assessment and mitigation strategies over most populous Indian megacity, Mumbai,
486 *Urban Climate*, 55, 101928–101928, <https://doi.org/10.1016/j.uclim.2024.101928>,
487 2024a.

488 Mangaraj, P., Sahu, S. K., Beig, G., Mishra, A., and Sharma, S.: What Makes the Indian
489 Megacity Chennai’s Air Unhealthy? - A Bottom-up Approach to Understand the
490 Sources of Air Pollutants, *Aerosol and Air Quality Research*, 24, 240089–240089,
491 <https://doi.org/10.4209/aaqr.240089>, 2024b.

492 Miller, S. M., Michalak, A. M., Detmers, R. G., Hasekamp, O. P., Bruhwiler, L. M. P., and
493 Schwietzke, S.: China’s coal mine methane regulations have not curbed growing
494 emissions, *Nature Communications*, 10, [https://doi.org/10.1038/s41467-018-07891-](https://doi.org/10.1038/s41467-018-07891-7)
495 7, 2019.

496 MoA & FW: Ministry of Agriculture and Farmers Welfare: Production Of Important Crops in
497 Three Largest Producing States in 2023-24* (Production in Million Tonnes) ,
498 Government of India, 2024.

499 MoEFCC: India Third Biennial Update Report to The United Nations Framework Convention
500 on Climate Change, 2021.

501 MoEFCC: Ministry of Environment, Forest and Climate Change, Measures to Reduce
502 Methane Emissions:
503 [https://pib.gov.in/PressReleaselframePage.aspx?PRID=1942106#:~:text=Government](https://pib.gov.in/PressReleaselframePage.aspx?PRID=1942106#:~:text=Government%20of%20India%20promotes%20green,2023)
504 [t%20of%20India%20promotes%20green, 2023](https://pib.gov.in/PressReleaselframePage.aspx?PRID=1942106#:~:text=Government%20of%20India%20promotes%20green,2023). last access: 7 September 2024.

505 Census of India 2011, National Population Register & Socio Economic and Caste Census -
506 India: <https://censusindia.gov.in/nada/index.php/catalog/42619>.

507 NOAA, Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases:
508 https://gml.noaa.gov/ccgg/trends_ch4.

509 Pandey, A., Sadavarte, P., Rao, A. B., and Venkataraman, C.: Trends in multi-pollutant
510 emissions from a technology-linked inventory for India: II. Residential, agricultural and
511 informal industry sectors, *Atmospheric Environment*, 99, 341–352,
512 <https://doi.org/10.1016/j.atmosenv.2014.09.080>, 2014.

513 Parashar, D. C., Mitra, A. P., Gupta, P. K., Rai, J., Sharma, R. C., Singh, N., Koul, S., Ray, H.
514 S., Das, S. N., Parida, K. M., Rao, S. B., Kanungo, S. P., Ramasami, T., Nair, B. U.,
515 Swamy, M., Singh, G., Gupta, S. K., Singh, A. R., Saikia, B. K., and Batua, A. K. S.:
516 Methane budget from paddy fields in India, *Chemosphere*, 33, 737–757,
517 [https://doi.org/10.1016/0045-6535\(96\)00223-8](https://doi.org/10.1016/0045-6535(96)00223-8), 1996.

518 Rosentreter, J. A., Borges, A. V., Deemer, B. R., Holgerson, M. A., Liu, S., Song, C., Melack,
519 J., Raymond, P. A., Duarte, C. M., Allen, G. H., Olefeldt, D., Poulter, B., Battin, T. I., and
520 Eyre, B. D.: Half of global methane emissions come from highly variable aquatic
521 ecosystem sources, *Nature Geoscience*, 14, 225–230,
522 <https://doi.org/10.1038/s41561-021-00715-2>, 2021.

523 Sahoo, P., Sahu, S. K., Mangaraj, P., Mishra, A., Beig, G., and Gunthe, S. S.: Reporting of
524 Gridded Ammonia Emission and Assessment of Hotspots across India: A

525 comprehensive study of 24 anthropogenic sources, *Journal of Hazardous Materials*,
526 479, 135557–135557, <https://doi.org/10.1016/j.jhazmat.2024.135557>, 2024.

527 Sahu, S. K., Mangaraj, P., Beig, G., Samal, A., Pradhan, C., Dash, S., and Tyagi, B.:
528 Quantifying the high resolution seasonal emission of air pollutants from crop residue
529 burning in India, *Environmental Pollution*, 286, 117165,
530 <https://doi.org/10.1016/j.envpol.2021.117165>, 2021.

531 Sahu, S. K., Mangaraj, P., and Beig, G.: Decadal growth in emission load of major air
532 pollutants in Delhi, *Earth System Science Data*, 15, 3183–3202,
533 <https://doi.org/10.5194/essd-15-3183-2023>, 2023a.

534 Sahu, S. K., Mangaraj, P., Beig, G., Lund, M. T., Samset, B. H., Sahoo, P., and Mishra, A.:
535 Development and comprehensive analysis of spatially resolved technological high
536 resolution (0.1°×0.1°) Emission Inventory of Particulate Matter for India: A step
537 Towards Air Quality Mitigation, *Earth System Science Data Discussion*,
538 <https://doi.org/10.5194/essd-2023-310>, 2023b.

539 Sahu, S. K.: Methane Emission Data [Data set]. Zenodo.
540 <https://doi.org/10.5281/zenodo.14089138>, 2024.

541 Sahu, S. K., Mishra, M., Mishra, A., Mangaraj, P., and Beig, G.: Quantification and
542 assessment of hazardous mercury emission from industrial process and other
543 unattended sectors in India: A step towards mitigation, *Journal of Hazardous*
544 *Materials*, 470, 134103–134103, <https://doi.org/10.1016/j.jhazmat.2024.134103>,
545 2024.

546 Samal, A., Sahu, S. K., Mishra, A., Mangaraj, P., Pani, S. K., and Beig, G.: Assessment and
547 Quantification of Methane Emission from Indian Livestock and Manure Management,
548 *Aerosol and air quality research*, 24, 230204–230204,
549 <https://doi.org/10.4209/aaqr.230204>, 2024.

550 Saunio, M., Bousquet, P., Poulter, B., Peregón, A., Ciais, P., Canadell, J. G., Dlugokencky,
551 E. J., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F. N.,

552 Castaldi, S., Jackson, R. B., Alexe, M., Arora, V. K., Beerling, D. J., Bergamaschi, P.,
553 Blake, D. R., and Brailsford, G.: The global methane budget 2000–2012, *Earth System*
554 *Science Data*, 8, 697–751, <https://doi.org/10.5194/essd-8-697-2016>, 2016.

555 Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B.,
556 Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K.,
557 Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K.
558 M., Carrol, M., and Castaldi, S.: The Global Methane Budget 2000–2017, *Earth System*
559 *Science Data*, 12, 1561–1623, <https://doi.org/10.5194/essd-12-1561-2020>, 2020.

560 Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P. A., Regnier, P., Canadell, J. G.,
561 Jackson, R. B., Patra, P. K., Bousquet, P., Ciais, P., Dlugokencky, E. J., Lan, X., Allen, G.
562 H., Bastviken, D., Beerling, D. J., Belikov, D. A., Blake, D. R., Castaldi, S., and Crippa,
563 M.: Global Methane Budget 2000–2020, *Earth System Science Data*, 17, 1873–1958,
564 <https://doi.org/10.5194/essd-17-1873-2025>, 2025.