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India's biomethane generation potential from wastes and the corresponding greenhouse gas emissions abatement possibilities under three end use scenarios: electricity generation, cooking, and road transport applications†

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This paper evaluates India's annual waste-to-energy potential through biomethane production, and the corresponding greenhouse gas abatement. Biodegradable wastes generated across various sectors (agriculture, horticulture, animal husbandry, municipalities, sericulture, fisheries, and industries) are examined, many of which have not been considered previously for India's bioenergy potential assessments. The degree of replaceability of present-day unclean fuels and the net avoided greenhouse gas emissions from the utilisation of this biomethane are evaluated for three separate end use scenarios: electricity generation, cooking, and road transportation. The total biomethane generation potential is 125 billion cubic metres, after considering a gas leakage rate of 3%. The corresponding total heat and electrical energy generation potentials are 4.49 EJ and 748.59 TWh respectively; the breakdown of this for all the states and union territories of India is also calculated. Biomethane from wastes could have provided for either 47% of India's gross generated electricity or 91% of India's road transport fuel demand in the financial year of 2018–19. Less than 43% of this biomethane could supply the entirety of the country's cooking fuel demand. The corresponding avoided GHG emissions from the displacement of fossil fuels and the prevention of crop residue field burning and municipal waste dumping are between 284 and 461 million tonnes of carbon dioxide-equivalent, excluding the contribution from black carbon. The avoided particulate emissions from crop residue burning prevention is around 2 million tonnes. Thus, this paper makes a strong case for biomethane generation from wastes in India to appropriately address climate change impact, pollution, and waste disposal problems, and aims to inform and influence energy policy in the country, with additional considerations of the gap between the potential and the state-of-the-art, and the technical and socio-economic challenges of waste-to-energy schemes. In addition to the quantitative evaluations, this paper contains a comprehensive compilation of data on waste and biomethane generation potentials from experiments and surveys scattered across the literature; it is hoped that this will be a valuable resource for future research, energy assessments, and policy considerations.

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1 Introduction

India is the world's seventh largest and second most populous country, with a population of 1.38 billion (in 2020).¹ The size and huge population give rise to several challenges. The first of these is that there is a high demand for energy: with one of the most rapid rates of development in the world,² India consumed 1210 TWh of electricity in the financial year of 2018–19,³ and the demand for crude oil is so high that India imports nearly 80%⁴ of the quantity consumed. Secondly, there is an asymmetry in

energy access: though the country is officially considered to have 100% electricity access after an excellent countrywide electrification drive by the government recently, almost 300 million people either still do not have electricity access or are unhappy with their electricity supply.^{5–8} This is because a village is considered electrified if all of its public places and 10% of its houses have access to electricity;^{5–8} also, some remote villages got left out of the electrification drive.⁵ Other prominent challenges are those of air pollution and waste management, chiefly agricultural residues and municipal solid wastes (MSW). With a countrywide MSW generation rate of nearly 163 million tonnes per day (in 2018–19),⁹ which increases at a mean rate of 5% per annum,¹⁰ urban waste management is considered a problem by many municipal authorities.¹¹

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These challenges in turn lead to significant environmental problems; India is not only a major contributor to global climate change and air pollution but is also drastically impacted by them. India is the world's third largest emitter of greenhouse gases (GHGs),¹² but the per-capita emissions are low compared to the global average,¹³ denoting again, an asymmetry in energy use and access. Existing energy sources are carbon-intensive and polluting: around 72% electricity is generated from coal.¹⁴ Current waste management practices are poor: about 72–90% MSW is left in open dumps with little or no processing,^{11,15} causing air, soil, and water pollution, methane emissions, and a spreading of foul odour and pathogens. The MSW collection efficiency is not 100% (though there has been considerable improvement since 2010, as detailed in previous studies.^{11,15}). Additionally, due to a lack of source segregation, biodegradables and plastics end up in the same garbage dumps almost throughout the country.^{16–18} Pollution from the field burning of crop residues (FBCR) causes largescale pollution, health, and visibility problems, disrupting the life and work of citizens, with considerable associated economic losses, especially in North India and around the National Capital Region.^{19–24} This FBCR also causes a loss of nutrients,^{23,25} kills beneficial soil microorganisms, and has adverse impacts on the soil nitrogen balance, leading to a gradual reduction in soil fertility.²³ However, burning is an easy and traditional practice for quick crop residue and orchard pruning waste management. Some of these are also burnt as solid biomass fuels (SBFs) for cooking (and a small part, as insect repellent), causing GHG and particulate matter (PM) emissions.²⁶

There is an opportunity to exploit municipal, agricultural, horticultural, and industrial wastes for energy generation, as noted in some previous studies.^{27–30} This could form part of the energy transition to low-carbon, non-polluting, and locally available energy sources to improve energy access, address climate change, and make India more self-reliant in energy supply. It would also address waste management difficulties. In order to enable such an energy transition, it is important to identify all available renewable and sustainable energy sources along with their geographical locations in the country. This will help in planning energy system expansions and the replacement of fossil fuels with cleaner energy sources.

In this paper, we assess the state-wise energy generation potential of organic wastes produced annually in India from all major sectors, *i.e.*, agriculture, horticulture, animal husbandry, industries (including sericulture and fisheries), and municipalities, through anaerobic digestion (decomposition by microorganisms in the absence of oxygen) to produce biogas. Our assessment is based on experimental results on biomethane generation from the literature and also includes a much more comprehensive list of wastes than previous studies; so, this study should estimate India's waste-to-energy (WTE) potential more accurately than previous publications that are usually based on assumed biogas yields for most substances. We also evaluate the degree of replaceability of existing unclean fuels in India with biogas, under three end-use scenarios, *i.e.*, electricity generation, cooking, and road transportation, and the corresponding annual GHG emissions

abatement potential, which add to the novelty of this study. The emissions avoided from the prevention of FBCR and MSW open dumping are also estimated. As part of the assessment, a comprehensive compilation of experimental results on characteristics and biomethane generation of many types of wastes was prepared, from the academic literature. This is included here to simplify future bioenergy assessments in India and other countries. Being a spatial (state-wise) energy potential assessment, it is hoped that this paper will inform policy framing by encouraging India's central and state governments towards greater WTE conversion, and also inspire similar energy research and transitions in other developing countries.

Biogas was chosen as the preferred energy generation route from wastes because it is the most efficient path for WTE conversion (even when compared with bioethanol),³¹ and several life cycle assessment (LCA) studies conclude that biogas generation and composting are the most effective and environmentally sustainable strategies for organic waste management.^{32–34} Biogas (mostly methane) is produced by anaerobic digestion (AD) (alongside digestate fertiliser) and undergoes clean combustion to emit only carbon dioxide (CO₂) and water vapour. This emitted CO₂ is biogenic, *i.e.*, it is part of the Earth's natural carbon cycle, and would be emitted during the usual aerobic (oxidative) decay of organic matter anyway, even on not producing and utilising biogas; thus, biogas burning does not add any additional carbon to the atmosphere. It is also worth noting that methane, which is a much more potent GHG, is only released during anaerobic decay of organic matter and not natural aerobic decay (some methane is released from large dumps due to anaerobic digestion in the deep layers because of a shortage of atmospheric oxygen supply; these would also be avoided on producing biogas). Biogas can thus displace fossil fuels and reduce the carbon impact of energy use. Energy extraction from wastes has lower environmental impact compared to other biomass energy sources, like growing dedicated energy crops³⁵ because wastes are ubiquitous and are generated irrespective of their use, often causing management problems. The environmental impacts of biogas generation are negligible,³⁶ even when the positive impacts of displacing fossil fuels and chemical fertilisers are not explicitly considered. Biogas is a renewable, sustainable, and ozone-layer-friendly energy source.³⁷ Additionally, the digestate that remains is a rich organic fertiliser and performs as good as synthetic fertilisers.³⁸ It can displace synthetic fertilisers in agricultural fields, potentially offsetting further, the environmental impacts of their manufacture.

2 Methods and data sources

2.1. Biomethane generation potential assessment

Biodegradable wastes generated from various sectors in India were identified as follows:

- Crop residues from agricultural and horticultural activities, including orchard pruning wastes.
- Wastes from the animal husbandry sector.
- Municipal solid wastes (MSW) from urban and semi-urban areas.



- Wastes from fisheries.
- Wastes from sericulture (silk production).
- Municipal wastewaters.
- Industrial wastewaters and solid (organic) wastes.

A wide array of sources in the literature relating to bioenergy in general, and these specific sectors in particular, were reviewed to compile data and methodologies for WTE potential calculations through anaerobic digestion.

Biogas is an energy-rich gaseous mixture consisting of methane (usually 50–75% by volume), carbon dioxide, and trace amounts of other gases like oxygen, nitrogen, hydrogen sulphide, and ammonia.^{39,40} Biogas is usually upgraded to the methane purity of natural gas; the trace gases, especially hydrogen sulphide and ammonia, are removed before use.^{41,42} Methane is the only combustible component in biogas; we refer to this as 'biomethane' henceforth, and obtain its volume directly, rather than that of biogas. This keeps calculations independent of the varying methane concentrations in biogas obtained from different substances.

In this paper, biomethane generation calculations are based on the volatile solids (VS) content of substances, defined as the amount of organic matter present in the material that biodegrades during anaerobic digestion to generate biogas.^{43,44} It may be mentioned as a percentage/fraction of the mass of the substance or its total solids (TS) concentration. The TS (total solids) or dry matter content of a sample is the net amount of solid material present in it; this remains after the moisture contained in the substance is completely removed, and is expressed as a percentage/fraction of the mass of the substance under consideration.^{43–45} If VS_{TS} is the VS content of a material expressed as a fraction of its TS, then the net volatile solids content (VS) is given by eqn (1).^{43,46}

$$VS = TS \times VS_{TS} \quad (1)$$

The volume of biomethane (V) generated from a substance is calculated using one of the eqn (2a)–(2c), depending on whether methane generation was available per unit mass of VS, TS, or fresh matter respectively (after Langeveld *et al.*⁴³):

$$V = W \times VS \times Y_{b,VS} \quad (2a)$$

$$V = W \times TS \times Y_{b,TS} \quad (2b)$$

$$V = W \times Y_{b,FM} \quad (2c)$$

Here, W = mass of available fresh (wet) wastes undergoing anaerobic digestion; VS = volatile solids content as a fraction of the mass of wastes, either available directly, or calculated using eqn (1) if available in terms of TS. TS = total solids content as a fraction of the mass of wastes. $Y_{b,VS}$ = biochemical methane potential (BMP) per unit mass of VS, *i.e.*, the specific cumulative biomethane yield per unit mass of VS over the entire period allowed for anaerobic digestion (called the hydraulic retention time, HRT⁴⁷); $Y_{b,TS}$ = corresponding BMP per unit mass of TS; $Y_{b,FM}$ = corresponding BMP per unit mass of the wastes or fresh matter (FM).

In this paper, the values of TS and VS were obtained from the academic literature. The TS values reported with respect to fresh/wet wastes (and not dry wastes) were used since production quantities were evaluated for wastes that are directly available; the masses will reduce on drying these, depending upon the moisture lost; moisture losses are not directly relevant to our study. The Y_b 's (BMPs in one of the forms) required in the above equations were sourced from published experimental results on waste mono-digestion, to account for the different methane yields of different substances and obtain dependable predictive quantitative estimates. Mono-digestion was considered even though co-digestion can slightly improve yields for some waste streams (like crop and animal wastes^{43,48–50}) because the simultaneous availability of wastes from different sources, and hence, the possibilities and extents of mixing, can vary spatially and temporally. The mixing ratios cannot be obtained for the whole country in this work and need to be determined for individual biogas plants depending on location, on a case-by-case basis. This makes our estimates slightly modest since multiple wastes are expected to be available together at many locations, but it also prevents overly optimistic results.

Furthermore, all the wastes generated from a particular source are not available for energy generation since some wastes have other competing uses. This is denoted by the waste or residue accessibility factor (or availability factor), which is the fraction or percentage of the total wastes available for a particular purpose (in this case, energy generation).^{29,51} The values of ' W ' in eqn (2) were obtained after accounting for waste availabilities, as explained in the following sections. Accessibility factors for wastes were obtained from the literature relating to India (as far as possible); the corresponding sources are mentioned in the respective sections.

There are three standard temperature ranges for anaerobic digestion: psychrophilic (25 °C), mesophilic (35 °C to 42 °C) and thermophilic (50 °C to 55 °C).^{39,47} All the experimental results used in this study pertain to mesophilic conditions. This temperature range is best suited for India as appreciable additional heating of the digester chambers will not be required in most parts of the country during most of the year. The process is also economical and operates smoothly without much attention, giving good yields of biomethane.^{47,52}

2.1.1. Agricultural and horticultural crop residues. Agricultural and horticultural activities generate huge quantities of wastes in India, being major occupations almost throughout the country. The possibility of using the residues of major Indian crops for energy generation through both, direct combustion and biogas production, has been previously studied by some researchers.^{27–29,46,51,53–56} These studies, particularly those that consider anaerobic digestion (which constitute the minority),^{27,28,46} mostly only focus on some major crops like cereals, pulses, and sugarcane, and do not analyse the spatial state-wise distribution of these WTE resources, as presented in this paper. We consider wastes from all crops grown in India that are mentioned in the Agricultural and Horticultural Statistics.^{57–59} Furthermore, this study is different in using distinct experimentally determined BMPs from the academic literature for each crop residue type. This was deemed necessary



for greater accuracy because the BMP varies widely across different crops, as may be observed from Table 8.

The residues produced from a particular crop are quantified by the residue-to-product ratio (RPR); it is the mass of residues produced per unit mass of the corresponding crop (or product),^{29,51,55} and is also called the residue-to-crop ratio (RCR). The multiplicative product of the annual crop production and the RPR, is called the total residue production (TRP).^{29,51} This TRP, when multiplied by the corresponding residue accessibility factor, gives the surplus residue production (SRP), which is the quantity of crop residues actually available for energy generation, with alternate uses accounted for.^{29,51} The SRP from each crop in a state was substituted for 'W' in eqn (2a) to obtain the corresponding annual biomethane generation; the sum over all crops gives the biomethane potential for each state. The RPRs, proximate characteristics (TS and VS), and BMPs of all crop residues included in this study are compiled in Table 8 in Appendix 1. The spatially different state-wise accessibility factors for all crop types were obtained from Hiloidhari *et al.*²⁹ which classifies the crops as 'cereals', 'oilseeds', 'sugarcane', 'horticulture', 'pulses', and 'others'. Cash crops and plantation crops do not fit into these categories and the accessibility factors for 'others' were used for them (except sugarcane). Distinct state-wise availability factors were used for different crop residues because they can vary by location and waste kind, depending on the type and extent of local use.

The types and state-wise quantities of agricultural and horticultural crops produced in India were obtained from the respective statistics published by the Indian Government^{57–59} (tea and coffee productions were obtained from the respective boards' statistics^{60,61} since these state-wise quantities are not reported in the Horticultural Statistics). These were taken for the Indian financial year of 2018–19 (starting in April 2018 and ending in March 2019) for agricultural products and 2017–18 for horticultural products, as state-wise horticultural statistics have not been published after 2017–18. The change in total horticultural production in 2018–19 from the 2017–18 value was less than 0.2%;⁵⁸ so, this difference of one year is expected to introduce very minimal inconsistency. Moreover, absolute correctness of the production data has little value as they will change slightly every year; so, the biomethane potential will not remain constant but should be similar over consecutive years under ordinary circumstances. Also, peels of fruits and vegetables were excluded because most fruit peels are expected to end up in residential/municipal and industrial (food-processing) wastes. Loose flowers were the only category in the Horticultural Statistics that were excluded because the RPRs could not be ascertained; also, some flowers may potentially be digested too after their use, which could entail a detailed (separate) study. In any case, their contribution to the total biomethane generation will not impact the obtained results appreciably, based on the relatively low production quantities.

The BMPs and proximate compositions were sourced from the same studies as far as possible. If multiple sources reported very similar values (examples include rice and wheat), the mean of all similar observations was used. Moreover, different studies use different HRTs. When taking the mean values, either

studies with similar HRTs were referred to, or yields from higher HRT experiments were scaled down if appropriately reported methane yield data (in days or weeks) were available. When experimental BMPs were not found for a particular crop, but the results of proximate analyses were available, a specific biogas yield of 300 m³ per tonne-VS was assumed with a methane content of 60%^{39,40,43,46} (indicated in Table 8). The BMPs, TS, VS, accessibility factors, and RPRs are potential sources of uncertainty. However, since these were obtained based on a detailed and comprehensive survey of the academic literature, such errors are expected to be negligible and the results obtained are dependable.

2.1.2. Orchard pruning wastes. The use of orchard pruning wastes for biogas generation is an understudied subject internationally. These wastes have not been considered for energy potential calculations in India previously, to the best of our knowledge. Being organic, these residues can be managed through anaerobic digestion to generate biomethane, which will also prevent their burning and use as SBFs, thus reducing pollutant and GHG emissions.

There is a dearth of RPR data for most trees. So, data on the production of pruning wastes per hectare (for Europe) for each orchard type sourced from Boer *et al.*⁶² were multiplied with the state-wise land areas on which the orchards are grown (from the Horticultural Statistics⁵⁹) to estimate the corresponding total quantity of pruning residues generated annually in each state. This was multiplied by the suggested availability factor of 0.8 for pruning residues^{63–65} to obtain the value of 'W' in eqn (2c). When the residue production for a particular tree was not found, the mean for other trees was used. These data were validated against the few available RPR values in the literature and were found to mostly agree well.^{63,66} The trees included and the corresponding residue production and RPR data are summarised in Table 9 in Appendix 1. The mean BMP of pruning residues was found to be 109 m³ per tonne-FM, as the average of olives,⁶⁷ hazelnut,⁶⁷ wood,^{68,69} and other fruit-tree residues.⁷⁰ So, eqn (2c) was useful here. There could be slight differences in pruning residue generation in India owing to different growing conditions and pruning practices and a study in India is suggested to quantify these more accurately. However, this is not expected to modify the biomethane potentials drastically; as was observed for agricultural wastes, the RPRs differ only slightly (and almost negligibly) in different countries.

2.1.3. Animal wastes. The state-wise energy generation potential of biogas from animal wastes in India has been evaluated in previously published papers;^{30,53} similar studies for other countries demonstrate a growing interest in this topic.^{37,71–80} While most papers assess the biogas generation from both animal excreta and slaughterhouse wastes (wastes generated from meat production), the latter are not included in the Indian studies;^{30,53} this gap is addressed in this paper. Furthermore, the waste generation quantities depend upon the live weights of the animals under consideration.^{30,37,53} Most studies across the world use the same values of animal weights.^{30,72–74,76} However, it is important to acknowledge the differences in weights of the same animal species in different countries/regions, owing to differences in breeds and other local



conditions. For example, the live weight of cattle can vary between 135 kg and 800 kg, and that of small ruminants between 30 kg and 75 kg.⁷¹ In this paper, the live weights of 35 breeds of cows, 9 breeds of buffaloes, 16 breeds of goats, 46 breeds of sheep, 5 breeds of horses, and 2 breeds of camels raised in India were used to find the average masses of the respective species in India.^{81–84} For poultry, this was not necessary because the masses themselves being small (between 1.5 kg and 1.8 kg), the variation in masses is not appreciable. The weighted averages of live weights of the corresponding animals would be more appropriate, but these could not be evaluated in the absence of adequate breed population data. There is not sufficient data on the live weights of Indian pigs in the United Nations Food and Agriculture Organisation (FAO) database or elsewhere, so the value of 80 kg from Kaur *et al.*³⁰ was used. Moreover, the quantity of wastes produced daily by large livestock is about 5–6% of their body weights, as mentioned by Avcioglu *et al.*;⁷¹ however, despite mentioning this and citing this source, most other papers use 9% for this value^{30,37,74,76} without an explanation. Although the difference of 3% is not that high, it significantly influences the final biogas yields because of the large numbers of cattle involved in the calculations; we hence used the value of 6%, as defined in Avcioglu *et al.*⁷¹

The mean values of specific waste generation factors, TS, VS, BMPs, and the corresponding availability factors are compiled from the literature in Table 10 in Appendix 1. The quantities of wastes generated in each state were obtained by multiplying animal populations (including those raised for meat production) from government data⁸⁵ with the corresponding specific waste productions mentioned in Table 10. These were multiplied by the availability factors and then substituted for 'W' in eqn (2c), since the BMPs of animal wastes were available per unit mass of fresh matter (FM) directly (as seen in Table 10).

For slaughterhouse wastes, standard values from the literature were used. The waste generation factors are 20.4% of the body weights for large livestock (cattle, buffaloes), and 28% for small livestock.^{37,71–74,76} In case of poultry, the corresponding value is 20%.⁸⁶ A biogas production of 300 m³ per tonne-FM was assumed for all slaughterhouse wastes, with a methane content of 60%.^{37,71–74,76} The accessibility factor was assumed to be 90% since almost all slaughterhouse wastes should be available for collection and treatment.

2.1.4. Municipal solid wastes (MSW). Saini *et al.*⁸⁷ studied the energy generation potential of 75 Indian cities using a combination of biogas generation and incineration techniques, mostly using data from the Central Pollution Control Board (CPCB) released in 2005.⁸⁸ No paper was found to evaluate the state-wise biomethane potential of MSW.

Here, we consider the organic fraction of MSW in India's states for estimating their biomethane potentials; the state-wise MSW production quantities for the financial year of 2018–19 were sourced from CPCB's recent report.⁸⁹ Results of experimental investigations on MSW characteristics, *i.e.*, fractional organic content and TS, in 69 cities across India are compiled in Table 11 in Appendix 1 (these were only used to estimate numeric parameters of wastes in the different states, but not to assess the energy generations in these cities, as ours is a state-

wise study). The organic content and TS of MSW in each state were obtained as the averages of the corresponding quantities in the cities situated in that state, since waste characteristics are influenced by local cultural practices and food habits, and show significant variations across cities (as also concluded by Saini *et al.*⁸⁷). The mean organic fraction of MSW in each state was substituted for 'W' in eqn (2b) to obtain the potential biomethane yields. Paper and textiles/fabric contained in MSW were excluded from this 'W' because they are expected to be recycled (after collection). The mean BMP of organic MSW is 350 m³ per tonne-TS, based on multiple experimental studies in the literature,^{90–94} which was used for $Y_{b,TS}$ in eqn (2b). Also, all the generated (organic) MSW in India were considered available for energy generation because these do not have appreciable alternate uses. The lack of source segregation is problematic for this; this is discussed later.

Since waste characteristics are dynamic,^{95,96} recent studies were preferred while compiling them; data from Saini *et al.*⁸⁷ and Kumar *et al.*¹¹ (or CPCB data from 2005 (ref. 88)) were used only when published experimental results were not found for a particular city (which was rare and is mentioned in Table 11). The mean content of biodegradables in India's MSW was observed to be considerably higher than that reported in Saini *et al.*⁸⁷ Most experimental investigations after 2005 record increasing shares of organic contents, especially in big cities.

2.1.5. Municipal wastewaters. Municipal wastewaters or sewage contain organic matter, which can be treated by anaerobic digestion to produce biogas.⁹⁷ This organic content is measured by the chemical oxygen demand (COD), which is the mass of oxygen required for the decay of organic matter present in a unit volume of water.⁹⁸ Thus the "mass of COD removed" is a measure of the quantity of organic matter removed. The methane yields per unit mass of COD removed ($Y_{b,COD}$) are comparable for different anaerobic reactor models (with similar HRTs); so, the mean of various observations in the literature was used. The mean rates of COD removal ($COD_{removed}$) and methane generation are 88%^{97,99–103} and 261 m³ per tonne- $COD_{removed}$,^{97,100,101,103} respectively. The average COD content of sewage is 314.9 mg L⁻¹, based on multiple experimental investigations in various Indian cities.^{104–110} The annual state-wise sewage generation in 2018–19 was obtained from Government data.¹¹¹ The total biomethane generation volume (V) from a particular volume of wastewater (W_{water}) is found using eqn (3):^{97,112,113}

$$V = W_{water} \times COD \times Y_{b,COD} \times COD_{removed} \quad (3)$$

Here, COD is the mass of COD present per unit volume of wastewater, $Y_{b,COD}$ is the biomethane yield per unit mass of COD removed, and $COD_{removed}$ is the fraction of COD removed during anaerobic digestion.

2.1.6. Wastes and wastewaters from industries, fisheries, and sericulture. The biomethane generation potentials of wastes and wastewaters from industries, sericulture, and fisheries, assessed using the same methodology as this paper, are presented in Dey & Thomson.¹¹³ State-wise biomethane yields are reported there for fish and sericulture wastes and for wastewaters



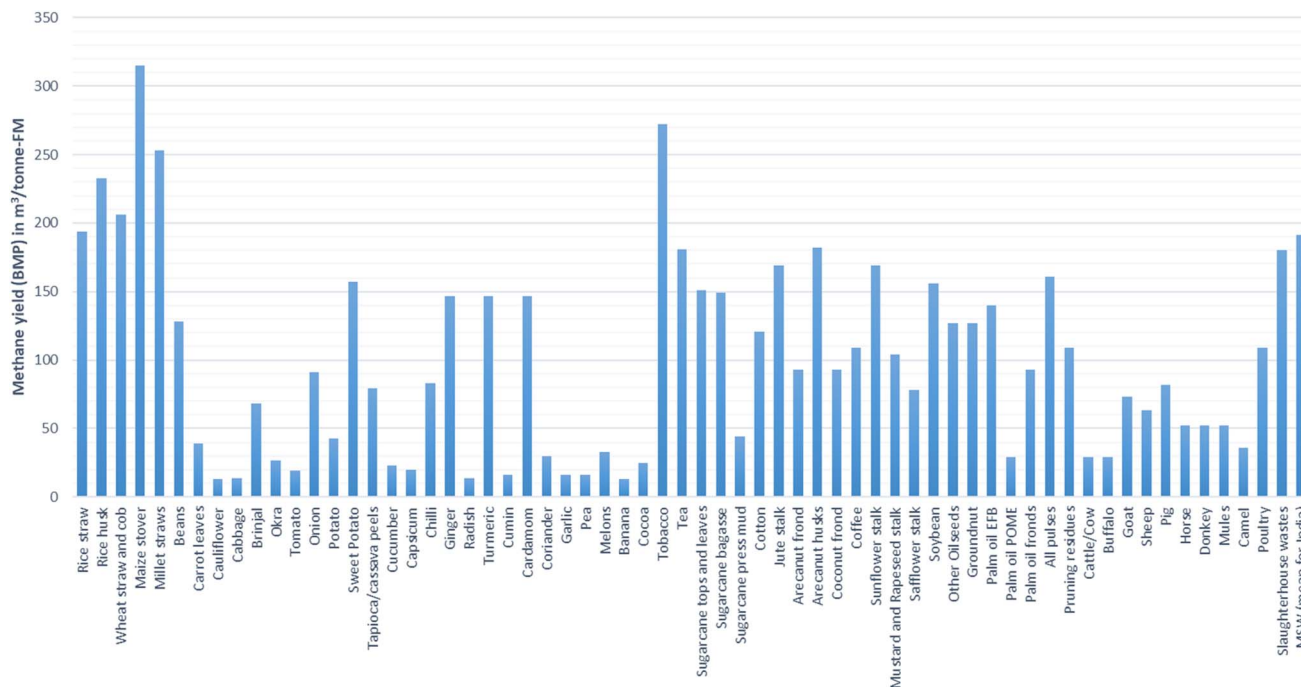


Fig. 1 Methane yields (BMP) per tonne of solid wastes (fresh matter); data and references in Appendix 1.

of slaughterhouses, palm oil mills, silk, and fish processing. These were added to the state-wise results in this paper (biomethane from palm oil mill effluent was added to the state-wise yields of 'oilseeds and palm oil' in agricultural wastes). For most other industrial wastes, the biomethane potential for the entire country has been reported by Dey & Thomson,¹¹³ owing to a lack of appropriate state-wise data; this value is 3113.9 million m³ and is added to India's total potential.

The biomethane potentials for each state and waste category obtained were summed up to calculate the total biomethane generation in the country. A visual comparison of the biomethane yields per tonne of fresh matter for all solid wastes considered in this paper (except industrial wastes, which have not particularly been compiled and assessed here) is presented in Fig. 1. It is seen that the methane yield per unit mass of fresh matter is usually greater for crop wastes than for animal wastes; so, increasing the utilisation of the former for biogas generation is highly beneficial.

2.2. Energy generation and emissions assessment

Three end use scenarios for biomethane were considered, to assess the potential of displacing fossil fuels and the consequent annual reduction in GHG and PM emissions. These are: electricity generation, cooking fuel, and road transportation fuel. An annual GHG emissions assessment was carried out to quantify the climate benefits of the GHGs avoided in one year on using biomethane (from wastes) to displace fossil fuels in India based on the 100 year global warming potentials (GWPs) of the GHGs involved, according to IPCC guidelines. The PM emission savings due to the avoidance of FBCR were also evaluated. Here, 'emissions' refer to both GHGs and PM, unless

explicitly clarified. Also, the terms 'GHG emissions' and 'carbon emissions' have been used interchangeably.

The system boundary for the emissions assessment is explained in Table 1, and the procedure to assess emissions, in the following subsections. All GHG emission conversions and comparisons were done considering a functional unit of 1 MJ of energy, electrical or thermal (the latter for cooking and transportation fuels). For electricity, the functional unit of 1 kWh was used too.

Here, the GWP of biogenic CO₂ (emitted on burning biomethane and crop residues) is considered zero. Any methane emissions were considered in the assessment since the 100 year GWPs of both, biogenic and fossil methane, are much greater than that of CO₂,¹²⁴ being 27 and 29.8 times respectively¹²⁵ (lower for biogenic since that carbon is still part of the natural carbon cycle). The GWP of nitrous oxide (N₂O) is 273, considering 100 years of cumulative forcing.¹²⁵

2.2.1. Emissions from biogas production and supply chain.

The net GHG impact of biogas plants per functional unit, was adapted from Singh *et al.*¹¹⁷ Moreover, methane leakages occur throughout the production and supply chain of biomethane, which were assumed to be 3% (as explained in Table 1). The emissions from leakage per functional unit were added to the GHG impact of biogas plants to obtain the total GHG emissions from biomethane per functional unit. This was compared with the GHG intensities of present-day energy sources to assess avoided emissions.

2.2.2. Fossil fuel displacement and avoided emissions.

Fossil fuel displacement and emissions from the three end use scenarios were analysed as follows (all related efficiencies and LCVs are listed in Tables 2 and 3).



Table 1 System boundary for emissions assessment

Process	Included (I) or excluded (E)	Reasons and notes
Emissions from the respective sectorial activities (like agriculture, animal husbandry, industrial units, <i>etc.</i>)	E	Should be allocated to the respective products or services
Transportation of MSW	E	Would occur even on not generating biogas from MSW
Transportation of crop residues to biogas plants	E	Would depend upon the individual biogas plants' transportation modes and waste sources, and the distances between the plants and these sources
Positive impacts of the field application of the digestate from biogas plants, thus displacing chemical fertilisers	E	Beyond the scope of this paper to assess the quantities of digestate produced, the related transportation required, and the acceptability of the digestate fertiliser to farmers
Particulate emissions from all activities involving the burning of fossil fuels like electricity generation and transportation	E	Beyond the scope of this paper to assess the degree of use of mitigation measures in India and the effectiveness of these measures
Handling and transportation of biomethane to end use consumers	E	It depends on how the biomethane supply chains are designed, and emissions can be kept really low if power plants are located adjacent to or very close to biogas plants, or if the cooking fuel is delivered to consumers in the vicinity of biogas plants and using eco-friendly modes of transport. Long distance transportation could be kept low, and the desired amounts could be transported by natural gas pipelines to minimise emissions. ¹¹⁴ Furthermore, in case of the use of biomethane as transport fuel, there is no need to consider these emissions because they will be eliminated too. Methane leakages during transportation are covered already in the 3%
GHGs involved in the construction and operation of biogas plants, including feedstock and digestate handling (not final use as fertiliser). These are collectively termed as the 'net GHG impact of biogas plants'	I	Though this impact is small and considered negligible by some authors, ^{115,116} it cannot be neglected fully, according to a study in India ¹¹⁷
Methane leakages across the supply chain of biogas	I	Leakages occur from the biogas plants and from upgradation and transportation activities. ^{118–120} About 1% methane leakage occurs from biogas plants. ^{118,119} The leakage from upgradation activities is technology-dependent: amine-based upgradation, water-based scrubbing, and membrane technology cause methane leakages of 0.04–0.07%, 1.97%, and 0.56% respectively. ¹²⁰ There may be further leakages during biogas transportation, bottling, and combustion. Based on these figures, a 3% cumulative methane leakage across the biomethane supply chain was assumed
Avoided GHG and PM emissions from the prevention of the field burning of crop residues	I	Using the crop residues as feedstocks for biogas generation prevents their field burning; the procedure is explained in section 2.2.3
Avoided methane emissions from municipal garbage dumps	I	Methane is released from municipal garbage dumps and landfills due to the anaerobic digestion of wastes in the deep layers where the supply of atmospheric oxygen is limited; ^{121–123} this is avoided on using up organic MSW for biogas generation. The procedure is explained in Section 2.2.3
GHG emissions avoided due to the displacement of fossil fuels by biomethane	I	This is the chief purpose of this paper; the procedure is explained in Section 2.2.2



Table 2 Lower calorific values of fuels

Fuel	Lower calorific value (LCV)	References
Methane	35.8 MJ m ⁻³ or 50 MJ kg ⁻¹	134–137
Natural gas	36.6 MJ m ⁻³	137
Petrol (gasoline)	44 MJ kg ⁻¹	138
Diesel (high speed diesel oil)	42.6 MJ kg ⁻¹	124
Liquified petroleum gas (LPG)	45.24 MJ kg ⁻¹	119
Kerosene	42.86 MJ kg ⁻¹	119

Table 3 Efficiencies of energy systems and engines

Energy system/engine	Efficiency (%)	References
Combined cycle power plant (CCPP)	60	126–129, 139 and 140
Methane cookstove	55	119
LPG cookstove	57	119
Kerosene cookstove	47	119
Petrol vehicle	36	141 and 142
Diesel vehicle	44	141–144
Methane/natural gas vehicle	38.2	145 and 146
LPG vehicles	45	147

Electricity. The biomethane was assumed to be combusted for electricity generation in combined cycle gas turbines (CCGTs), which have the highest efficiencies (in the range of 60–65%) based on the lower calorific value (LCV) of the gaseous fuel.^{126–129} India generated 1584 TWh and consumed 1210 TWh of electricity in 2018–19 (ref. 3) with an average carbon intensity of 675.1 gCO₂eq./kWh;¹³⁰ the generation potential and GHG impact of electricity from biomethane were juxtaposed against these values. There is a minor inconsistency in the electricity generation data available from the IEA¹⁴ and the Indian Government;³ we preferred the latter and used IEA data only when something was unavailable in the Government Statistics (results were unaffected by this; only the discussion of the state-of-the-art required data from both sources).

Cooking fuel. The total final thermal energy used for cooking from a particular fuel in India was evaluated by multiplying its LCV with the corresponding cookstove/burner efficiency (Table 3) and its quantity consumed (for biomethane, the quantity available) annually. The LPG and kerosene consumptions for cooking in India in 2018–19 in the domestic and commercial sectors were sourced from India's Government Statistics,¹³¹ while PNG (piped natural gas) use was deduced using Government¹³¹ and IEA¹⁴ data on natural gas use as cooking and transportation fuels. Therefore, the degree of displacement of these fuels by biomethane was estimated. Additionally, the annual per capita final energy consumption for cooking in India is around 0.77 GJ (as of 2019).¹³² This was multiplied by India's population in 2019 (ref. 1) to estimate the net annual cooking

fuel demand in the country, to compare with the final thermal energy available from biomethane. In the process, the approximate extent of use of SBFs like crop residues, cattle dung cakes, and wood, for cooking in India, was quantified (which is absent in reports and the literature).

To assess the GHG savings, GHG emissions from the life cycle stages of LPG and kerosene were adapted from Garg *et al.*¹¹⁴ For natural gas, the GHG intensity was adapted from Agrawal *et al.*¹³³ The GHG savings from the displacement of SBFs (chiefly methane, N₂O, and also black carbon, as CO₂ would still be biogenic), coal, and charcoal used for cooking have not been assessed here due to the unavailability of recent data on their usage and types, after the countrywide LPG drive.

Road transportation fuel. The purified and upgraded biomethane could alternatively be used as a fuel in road vehicles. The quantities of petrol, diesel, and LPG used for road transportation in India in 2018–19 are available in India's Petroleum Statistics,¹³¹ while the corresponding energy use from natural gas was taken from IEA data.¹⁴ The LCV of each transportation fuel was scaled down by the maximum brake thermal efficiency of the corresponding automobile engine (Table 3) and multiplied with its quantity consumed/available annually, to approximate the energy it provides to road vehicles in India. These were compared to find the quantities of present-day fuels that could be displaced by biomethane. The life cycle GHG emissions per MJ of final energy consumed from petrol, diesel, and LPG in India (for transportation purposes) were evaluated from Garg *et al.*,¹¹⁴ and those of CNG (compressed natural gas) from Agrawal *et al.*¹³³ Our results on GHG savings are modest and the actual on-road emissions are expected to be higher than our estimates as these are the maximum engine efficiencies, so, the true fuel consumptions are higher, rendering greater emissions.

2.2.3. Other avoided emissions

Crop residue burning. The use of agricultural wastes for biomethane generation will prevent their field burning. The avoided emissions from this were estimated based on mean values of emission factors (EFs, in g kg⁻¹) from the literature.^{148–155} No experimental investigations to estimate emission factors from FBCR in India were found. While Ravindra *et al.*¹⁴⁸ do quantify the atmospheric emissions from FBCR in India, they use emission factors from measurements conducted in other countries. Thus, there was no reason to prefer the results of one paper to another, and the mean values of EFs from multiple studies in the literature^{148–155} were used.

Other studies indicate that residues of only certain crops undergo field burning in India;^{25,148} the same was assumed in this paper (Table 4). Orchard pruning residues should be included here too, but the fraction of these burnt for clearing or cooking cannot be ascertained in the absence of data; they were thus excluded.

CO₂ has not been considered while estimating the global warming impact of FBCR burning as these emissions also constitute biogenic carbon. Black carbon (BC) also influences climate change,¹⁵⁶ and has been considered separately to estimate the climate impact since it is usually not included in other GHG assessments. Its 100 year GWP is 680–730 times that of



Table 4 Mean values of emission factors (EFs, in g kg⁻¹) for crop residue burning and other related details obtained from the literature^{148–155}

Pollutant details	Rice	Wheat	Maize/corn	Millet	Pulses	Oilseeds	Sugarcane	Cotton	Jute
PM _{2.5} (EF)	7.52	6.76	9.10	4.10	9.54	11.50	3.91	6.42	6.55
PM ₁₀ (EF)	5.03	6.24	5.62	4.30	8.80	8.05	4.83	7.84	4.35
CH ₄ (EF)	3.57	2.45	3.21	4.40	2.90	3.00	2.08	3.50	4.08
N ₂ O (EF)	0.48	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
Black carbon (EF)	0.40	0.54	0.63	0.70	0.72	1.70	0.65	0.72	0.70
Burning efficiency	0.89	0.86	0.92	0.90	0.90	0.82	0.68	0.90	0.90
Accessibility factors ²⁹	0.29	0.29	0.29	0.29	0.38	0.30	0.39	0.38	0.38
IPCC fraction of residues burnt ¹⁴⁸	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

CO₂ (ref. 157 and 158) (the lower value of 680 was used). The climate impact of BC emitted from FBCR only has been assessed in this paper.

MSW open dumping. Emissions from the open dumping of MSW in India (which are expected to be avoided on producing biomethane from MSW) were estimated using the IPCC default methodology,^{121,159,160} with an assumed correction factor to better represent the true methane emissions and ensure that the obtained savings are conservative. The method, along with the associated uncertainties, is described in Appendix 2.

These additional emission savings (from prevented FBCR and MSW dumping) were added to the avoided emissions from the displacement of fossil fuels to obtain the total avoided emissions.

3 Results and discussions

3.1. Waste to biomethane potential assessment

Animal wastes are found to produce the largest volumes of biomethane in India, followed by agricultural and horticultural residues, as can be seen in Table 5 (greater detail on the biomethane yields for each category of crops and animal wastes are presented in the ESI†). The larger states with higher populations, more agriculture and animal husbandry, and consequently higher waste generations, are the larger biomethane producers too. The state of Uttar Pradesh thus has the highest biomethane potential, followed by Madhya Pradesh, Maharashtra, Rajasthan, Bihar, and West Bengal. The union territories like Goa and Puducherry have low biomethane yields.

The energy available from this biomethane, after considering a methane leakage of 3% during storage, upgradation, and transportation, can displace present-day fuels and electricity, as evaluated in Tables 6 and 7. Table 6 also denotes the gap between the potential and the state-of-the-art. The electrical energy from this 125.46 billion m³ of biomethane (=748.59 TWh) can supply 47% of the electricity generated in the country (based on the gross generation of 1585 TWh in the financial year of 2018–19 (ref. 3)), and is numerically equal to 62% of the country's net electricity demand (1210 TWh (ref. 3)). Currently, the installed capacity of biomass and WTE generators is only sufficient to capture 12% of the potential.

It is interesting to note the biomethane yields from the sectors mostly neglected in previous studies on India's bio-energy potential: 2676.1, 13 348, 739.21, 273, 88.75, and 3113.9 million m³ of biomethane (excluding leakages) from wastes of

horticultural crops, cash crops, slaughterhouses, fisheries, sericulture, and industries respectively. These contribute 16% to the total electrical energy potential.

The biomethane can alternatively be used as a fuel for cooking or road transportation instead of electricity generation. Fig. 2 illustrates the proportion of the total final thermal energy potential of biomethane that would be needed to meet India's total energy demand for each of the respective sectors, adjusted according to the efficiencies of the cookstoves and engines. If all the biomethane is used in transportation, it would be able to displace 94% of the dirtiest petrol and diesel and about 91% of the total, when LPG and CNG are included (derived from Fig. 2). On the other hand, only about 43% of the biomethane would be needed to displace 100% of the cooking fuels used in the country; the remaining biomethane still being available for other applications. If SBFs, coal and charcoal are not considered, less than 32% of the biomethane is needed to displace the popular cooking fuels of LPG, PNG, and kerosene, in India.

3.2. GHG and particulate emissions assessment

The total GHG impact of biogas plants was found to be 691 gCO₂eq./m³-CH₄, including the methane leakage of 3% throughout the supply chain but excluding the emissions that occur during the transportation of feedstocks to biogas plants. Almost 84% of the emissions come from methane leakages, so reducing leakages to below 3% would be greatly beneficial in terms of climate impact and biomethane availability.

Fig. 3 shows the relative environmental performances of all cooking and transportation fuels based on the corresponding maximum cookstove/engine thermal efficiencies (brake thermal efficiencies for vehicle engines). This includes an estimate of the GHG emissions from using biomethane for that particular application based on typical burner/engine thermal efficiencies. The emission savings per MJ from the displacement of each fuel with biomethane, can be easily obtained from Fig. 3 by subtraction.

In Fig. 3, the mean GHG intensity of the existing transport fuels combined is weighted according to the consumptions (by gross energy) in India, of the four fossil fuels mentioned. This is dominated by the carbon intensities of petrol and diesel, as these are the dominant fuels for transportation in India, such that the mean emissions remain 193 gCO₂eq./MJ if LPG and CNG are neglected. Petrol vehicles are the worst with respect to GHG impact (based on engine performance), although diesel causes greater emissions



Table 5 State-wise annual biomethane generation potential from wastes and wastewaters across various sectors

State/union territory	Methane in million ^a m ³					Sericulture ^c (including processing wastewaters) ¹¹³	Total
	Agriculture and horticulture wastes	Animal wastes (including slaughterhouse wastes and wastewaters)	MSW	Municipal wastewaters	Fisheries ^b (including processing wastewaters) ¹¹³		
Andhra Pradesh	2391.8	2573.2	197.06	75.790	53.590	20.330	5311.7
Arunachal Pradesh	11.790	132.11	8.3800	1.320	0	0.1000	153.70
Assam	648.05	2077.7	51.270	18.560	0	8.9100	2804.5
Bihar	2545.9	4575.0	79.470	49.600	0	0.1400	7250.1
Chhattisgarh	771.43	1853.6	55.990	25.110	0.1600	0.9800	2707.2
Goa	0.2600	22.620	7.7700	3.8300	0	0	34.480
Gujarat	2164.9	4081.9	392.40	108.74	84.450	0	6832.4
Haryana	2943.3	1376.0	157.15	37.300	0	0	4513.8
Himachal Pradesh	141.59	573.59	9.4800	2.9000	0	0.0900	727.88
Jammu, Kashmir, and Ladakh	87.990	634.70	37.510	14.440	0	0.3200	781.06
Jharkhand	150.51	2215.2	106.25	33.530	0	6.4600	2536.8
Karnataka	3259.1	2642.9	507.08	99.710	15.200	31.510	6524.2
Kerala	288.68	510.58	154.24	67.370	29.170	0.0500	1050.3
Madhya Pradesh	4871.4	5173.0	222.70	84.850	0	0.2200	10 353
Maharashtra	4505.0	4124.3	812.20	214.97	25.340	1.4100	9682.7
Manipur	9.8300	75.290	8.0300	3.4800	0	0.8200	98.600
Meghalaya	15.970	213.52	4.2600	2.5100	0	1.9800	236.44
Mizoram	16.650	37.440	8.0700	2.3800	0	0.1600	65.630
Nagaland	21.500	61.590	7.4900	2.4300	0.1600	1.1000	93.530
Odisha	1001.0	1905.5	52.240	29.590	10.140	0.3500	2998.5
Punjab	4208.7	1519.5	137.30	43.930	0	0.0100	5909.4
Rajasthan	2760.9	5350.3	205.68	72.230	0	0	8389.1
Sikkim	7.4900	44.020	2.9900	0.6300	0	0	60.730
Tamil Nadu	2694.6	2972.8	510.14	147.81	29.940	5.6300	6355.9
Telangana	3019.4	1857.1	368.76	44.110	1.3800	0.6100	5290.9
Tripura	25.380	154.20	18.090	4.0700	0	0.1800	202.52
Uttar Pradesh	11 831	10 399	537.58	188.07	0	0.7800	22 955
Uttarakhand	288.90	554.03	64.940	13.070	0	0.1000	927.41
West Bengal	2488.9	3790.3	472.86	123.20	17.190	6.5100	6892.5
Andaman and Nicobar	0	13.880	2.4800	0.5800	1.3800	0	18.320
Chandigarh	0	5.9800	16.440	4.3300	0	0	26.750
Daman, Diu, D & N Haveli	0	6.9000	3.0000	1.4600	3.9900	0	15.350
Delhi	0	60.430	539.29	109.69	0	0	709.41
Lakshadweep	0	1.1200	1.3900	0.2100	0.3000	0	3.0200
Puducherry	0	22.240	15.850	3.5900	0.3000	0	41.980
Others ^c	3672.8	0	0	0	0	0	3672.8
Total	56 844	61 611	5775.8	1635.4	272.69	88.750	126 228

^a The results are rounded off to 5 significant figures. ^b These are from the results of Dey & Thomson¹¹³ and were not obtained in the analysis in this paper, but were used here. ^c The Agricultural Statistics^{57,58} do not mention the quantities of all crops grown in each state, but only give data for the major states. The category 'others' refers to the agricultural produce not allocated to any particular state, and is the cumulative production of all the states not explicitly mentioned.



Table 6 State-wise annual thermal energy and electricity generation potentials (2018–19) from biomethane and comparisons with the WTE state-of-the-art

State/union territory	Annual biomethane after 3% leakage (million m ³)	Annual gross heat energy potential ^a (PJ)	Resultant annual electrical energy potential ^a (TWh)	Potential electric power installation capacity ^a (MW)	Biomass power and WTE installed capacity in MW (March 2021) ¹⁶¹	Harnessed in biomass and WTE (% of biogas energy potential)
Andhra Pradesh	5152.4	184.46	30.742	3509.4	506.83	14.44
Arunachal Pradesh	149.09	5.3374	0.8896	101.55	0	0
Assam	2720.4	97.390	16.232	1852.9	2	0.11
Bihar	7032.6	251.77	41.961	4790.1	124.7	2.60
Chhattisgarh	2626.0	94.012	15.669	1788.7	244.9	13.69
Goa	33.450	1.1975	0.1996	22.780	0.34	1.49
Gujarat	6627.4	237.26	39.344	4514.1	77.3	1.71
Haryana	4378.4	156.75	26.125	2982.3	211.86	7.1
Himachal Pradesh	706.04	25.276	4.2127	480.90	9.2	1.91
Jammu, Kashmir, and Ladakh	757.63	27.123	4.5205	516.04	0	0
Jharkhand	2460.7	88.093	14.682	1676.1	4.3	0.26
Karnataka	6328.5	226.56	37.760	4310.5	1888.3	43.81
Kerala	1018.8	36.471	6.0790	693.90	2.27	0.33
Madhya Pradesh	10 043	359.53	59.922	6840.4	122.75	1.79
Maharashtra	9392.2	336.24	56.040	6397.3	2596.99	40.6
Manipur	95.640	3.4239	0.5707	65.140	0	0
Meghalaya	229.35	8.2107	1.3685	156.22	13.8	8.83
Mizoram	63.660	2.2790	0.3798	43.360	0	0
Nagaland	90.720	3.2478	0.5413	61.790	0	0
Odisha	2908.6	104.13	17.354	1981.1	59.22	2.99
Punjab	5732.1	205.21	34.202	3904.3	484.2	12.4
Rajasthan	8137.4	291.32	48.553	5542.61	121.25	2.19
Sikkim	58.910	2.1090	0.3515	40.130	0	0
Tamil Nadu	6165.2	220.72	36.786	4199.3	1019.05	24.27
Telangana	5132.1	183.73	30.622	3495.6	205.9	5.89
Tripura	196.44	7.0326	1.1721	133.80	0	0
Uttar Pradesh	22267	797.14	132.86	15 166	2117.26	13.96
Uttarakhand	899.59	32.205	5.3676	612.73	0	0
West Bengal	6685.8	239.35	39.892	4553.9	319.92	7.03
Andaman and Nicobar	17.770	0.6362	0.1060	12.100	0	0
Chandigarh	25.950	0.9290	0.1548	17.680	0	0
Daman, Diu, D & N Haveli	14.890	0.5331	0.0888	10.140	0	0
Delhi	688.13	24.635	4.10 584	468.70	52	11.09
Lakshadweep	2.9300	0.1049	0.0175	2.0000	0	0
Puducherry	40.720	1.4578	0.2430	27.740	0	0
Total^b	122 441	4383.4	730.57	83 398	10 184	12.21^c

^a Gross heat energy refers to the total heat available on combusting all the biomethane generated annually; electrical energy refers to the electricity available annually when all this heat is converted to electricity in a combined cycle power plant (at 60% efficiency). Electric power is the instantaneous power that can be generated throughout the year based on the generated electrical energy and gives an idea of the desired installed capacity for waste-to-electricity (WTE) generation. ^b Also includes the generation from 'others' (states) for agricultural wastes, which include the states not explicitly mentioned in the agricultural statistics; so, the total does not directly add up from the column. This also excludes industrial wastes and wastewaters, other than palm oil mills, fisheries, sericulture, and slaughterhouses. The cumulative results on including all industrial wastes and wastewaters are presented in Table 7. ^c This becomes 11.92% on considering all industrial wastes and wastewaters from the next table.

Table 7 Important cumulative results

Annual biomethane generation from all sectors except industries, from the state-wise study (billion m ³) after considering 3% leakage	122.44
Biomethane generation from industrial wastes and wastewaters (million m ³) after considering leakage (except POME and wastewaters from slaughterhouses, fish and silk processing) ¹¹³	3020.5
India's total biomethane potential from wastes (billion m ³), after accounting for leakage	125.46
Total heat energy available from biomethane annually, based on LCV (in PJ)	4491.5
Average electric power potential (in GW)	85.455
Total annual electrical energy potential (in TWh)	748.59

based on gross energy generation. LPG emits the least GHGs among the fossil fuels used for transportation, followed by CNG. This is reversed in the case of cooking fuel, where PNG is the least carbon-intensive fossil fuel; this is attributable to the higher efficiencies of natural gas cookstoves as compared to vehicle engines. All these fossil fuels emit non-biogenic CO₂ on burning, which could be replaced by biogenic CO₂ on using biomethane. The GHG emissions that occur during the extraction and refining of the fossil fuels would also be avoided.

Using the functional unit of 1 kWh for electrical energy, the GHG emissions from India's electricity grid are 675.1 gCO₂eq./kWh and those from biomethane are 115.8 gCO₂eq./kWh. Thus, biomethane can save about 559.3 gCO₂eq./kWh (of electricity generated).

Crop residue burning annually generates between 37.41 million tonnes of CO₂-equivalent (using IPCC burning fraction data¹⁴⁸) and 43.68 million tonnes of CO₂-equivalent (using SRP²⁹) of GHGs in

the form of methane and nitrous oxide. If black carbon is included, the GHG emissions increase to between 100.8 million tonnes of CO₂-equivalent (IPCC) and 114.52 million tonnes of CO₂-equivalent (SRP). Additionally, the lower and upper limits for PM_{2.5} emissions from FBCR are 1019 and 1159 thousand tonnes. The corresponding values for PM₁₀ are 814 and 943 thousand tonnes. These emissions can be eliminated if biomethane is produced from these crop residues, also noting that negligible amounts of particulates are released during the construction of biogas plants and the combustion of the gas.¹¹⁹ This PM reduction has direct benefits for public health and the economy. Biogas schemes can also indirectly improve solar energy yields by reducing atmospheric PM concentrations, thus contributing further to sustainable energy transitions and climate change mitigation.¹⁶²

Methane emissions from the open dumping of MSW generated annually (calculated in Appendix 2) are 4.49 million tonnes of CO₂-equivalent (=234 million m³ of methane). Without using the correction factor (Appendix 2), these GHG emissions are 20.21 million tonnes of CO₂-equivalent; the former is used here to obtain less optimistic estimates for avoided emissions. These emissions can be avoided on converting biodegradable municipal wastes into biomethane, or at least capturing landfill gas. The former is a better option as the yields of methane are higher on conducting anaerobic digestion in a biogas plant, under conditions that are more suitable for methane generation, as can be observed from Table 5.

The GHG savings on replacing present-day fuels with biomethane, and adding the corresponding cumulative savings achievable on eliminating FBCR (using IPCC burning fraction data, which are conservative) and MSW open dumping, are illustrated in Fig. 4. For cooking fuels, the values include the complete displacement of LPG, PNG, and kerosene only, while the emission savings from displacing all SBFs, coal, and charcoal were excluded for lack of appropriate data. So, greater emission savings are to be expected from the cooking sector.

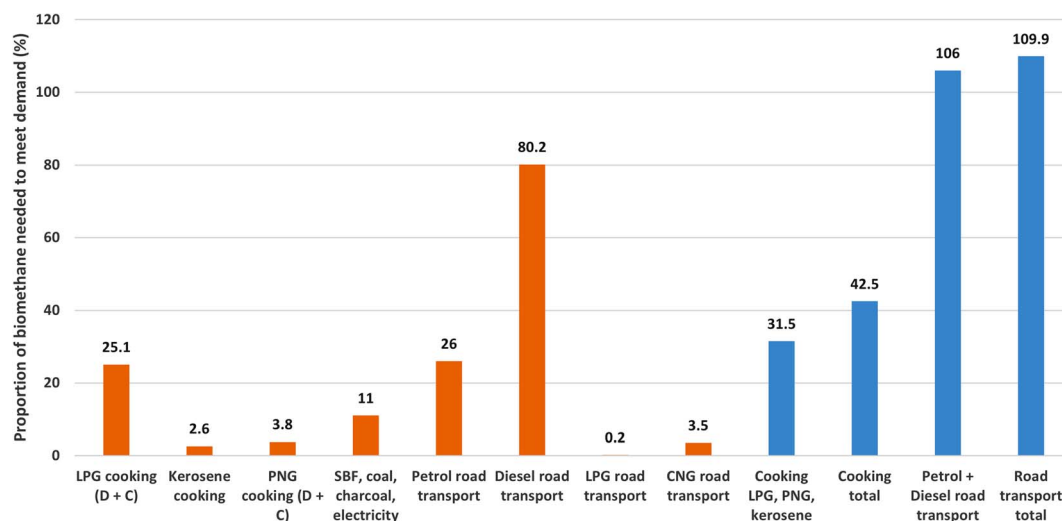


Fig. 2 The proportion of the maximum potential biomethane production needed to meet the heat energy demand of each traditional fuel in India's cooking and transportation sectors in 2018–19. This includes Liquefied Petroleum Gas (LPG), Piped Natural Gas (PNG) and Solid Biomass Fuels (SBF). Note that (D + C) means domestic and commercial sectors.



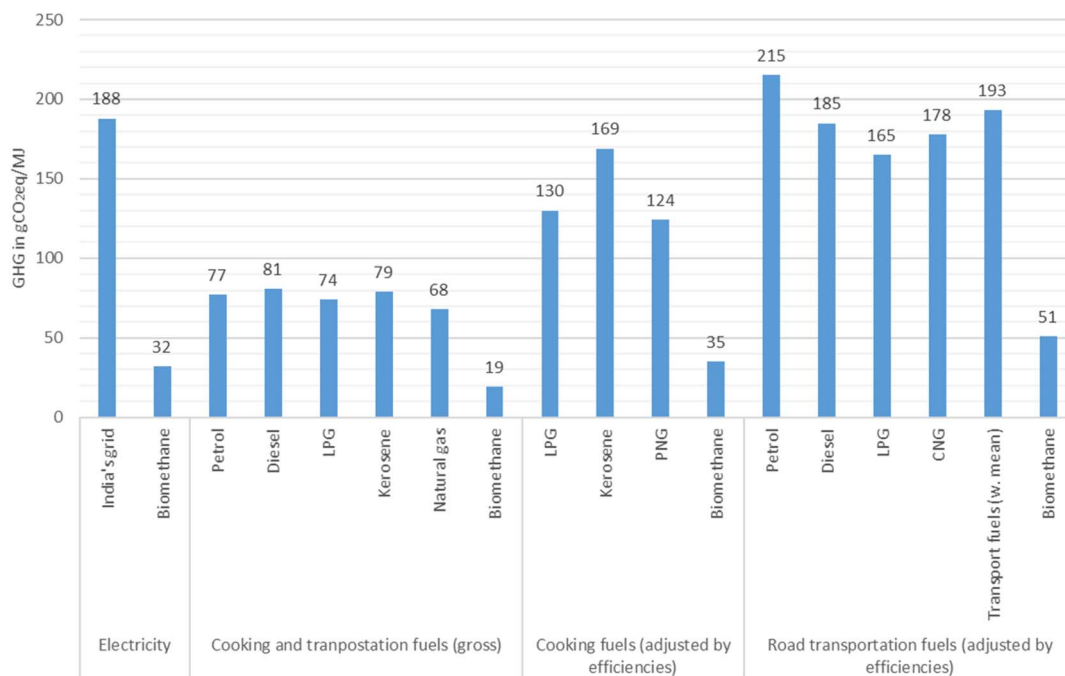


Fig. 3 Comparison of GHG emissions from traditional fuels and biomethane, and the corresponding emissions avoided on using biomethane, both based on gross energy available and adjusted according to burner/engine thermal efficiencies (does not include black carbon); w. mean = weighted mean (according to gross energy consumption from those fuels).

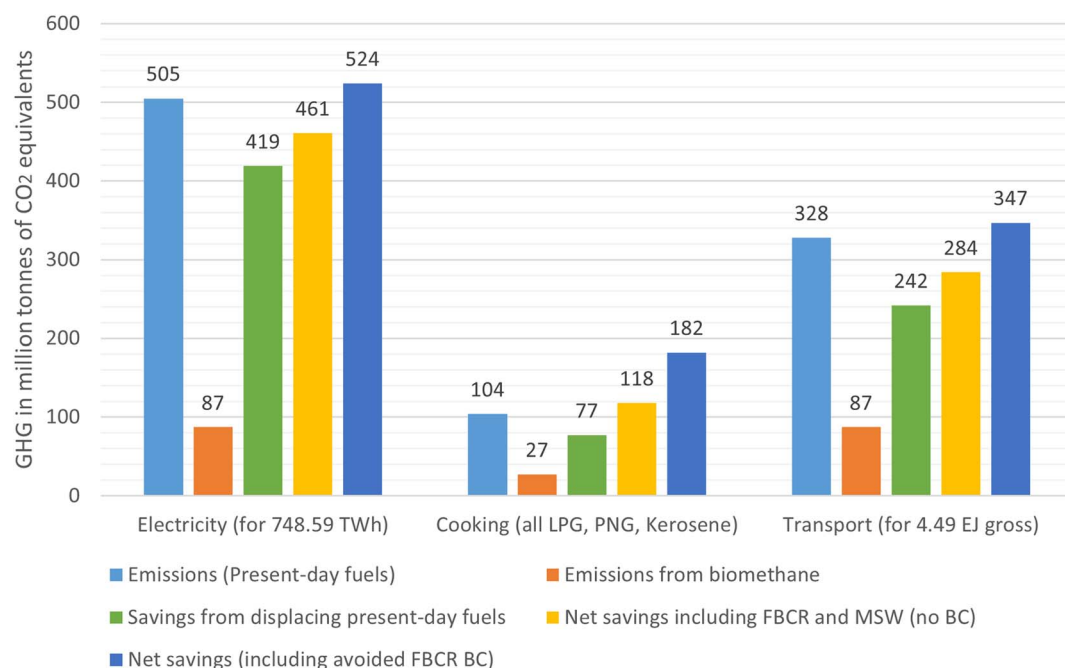


Fig. 4 Cumulative annual GHG emissions avoided on using biomethane, considering the displacement of present-day fuels, and including the emissions avoided from crop residue burning and MSW open dumping (additional 284 million tonnes of savings for using the biomethane remaining after cooking fuel application (*i.e.*, 68% of the total generated biomethane), for electricity generation). Note: the black carbon avoided is only from the FBCR circumvented; it does not include avoided black carbon from fossil fuel burning.

The avoided cumulative emissions are highest for the electricity sector, followed by the road transportation sector. This has to do with the greater gross consumption of energy as electricity, compared to transportation and other fuels in India

annually, and the high carbon intensity of electricity generation owing to the predominance of coal. It is also noteworthy that cooking fuel displacement denoted in Fig. 4 constitutes 32% of the energy potential of biomethane only (since SBFs, coal, and

charcoal are excluded here). If the remaining biomethane is used for electricity generation, it will additionally save 284 million tonnes of CO₂-equivalent, which can be added to the savings from cooking to reflect the impact of all the available biomethane. This would raise the total GHG savings from cooking (+electricity generation) to 402 million tonnes (without BC) and 466 million tonnes (including avoided BC from FBCR), *i.e.*, greater than the savings from transportation.

3.3. Limitations and validation

The results presented in this paper are only for a snapshot of one year, *i.e.*, the financial year of 2018–19. While this is a limitation, the paper gives a comprehensive idea of the annual energy generation potential from wastes in India's states and the whole country, and the corresponding GHG abatement. The results are sensitive to changes in annual waste and biomethane production rates from the various sectors, which change every year, but the differences are not expected to be extremely large; for instance, the yearly variation in food grain production in India has typically been below 6% since 2005, and less than 1% for some consecutive years.^{57,58} (Horticultural products show a similar trend of annual increase.⁵⁹) Furthermore, the biomethane generation potential is not expected to reduce, but rather increase with future increases in population, GDP (and thus higher standards of living), agricultural produce, and industrial output. This trend is already visible in the data; for example, food grain production has generally shown an increase over the last 5 decades in India, owing to an increase in both production areas and yields.^{57,58} It is thus expected that a re-analysis using averaged historical data over several years would further underestimate the biomethane potential.

The accessibility factors of crop residues and animal wastes used here already consider the reduction in available material due to some being already allocated to alternate usages, including composting. Since biogas generation will also produce digestate fertiliser, using wastes for biogas generation rather than composting could be better for sustainability and profitability; consequently, the biomethane potentials could increase beyond those calculated here. Using biogas digestate to replace synthetic fertilisers would further raise the GHG savings from the findings of this paper, by removing the emissions incurred for their production.¹⁶³

The reported GHG emissions from biogas plants (and thus the abatement potential) are also sensitive to the biomethane leakage rates since the leakages constitute most of the life cycle GHG emissions. As detailed in Section 2.2, a methane leakage rate of 3% was assumed for this study. This is on the higher side for biogas plants,¹¹⁹ but expectedly realistic (also giving modest and less optimistic abatement) based on emissions from upgradation and transportation.¹²⁴ Further data on real leakage rates for installations and pipelines in India would be needed to confirm these values. Also, for our assessment, the GHG impacts of construction of a biogas plant that generates electricity from sewage were adapted from Singh *et al.*¹¹⁷ A full LCA of biogas plants for different kinds of feedstocks and locations

is missing and is suggested as further study; this can further improve the accuracy of the obtained GHG emissions and abatement potential, since multiple waste streams are typically involved.

No additional GHG impacts are considered from the actual emissions that occur while transporting wastes to biogas plants and then biomethane to the end user (except for the leakage mentioned previously). While the inclusion of these would give better estimates of GHG abatement, care would need to be taken to avoid double-counting the transportation impacts of wastes (which might be attributed to the life cycle of the consumed product, rather than its waste). Furthermore, transport distances are dependent on plant location, which requires further design of WTE infrastructure in India. Strategically locating biogas plants based on either the availability of waste resources or the proximity to end users, could maintain very low transportation GHG emissions and render the true emissions to be very close to these estimates.

The avoided BC emissions discussed in Section 3.2 consider only the BC avoided from FBCR; there will be additional BC avoidance from all fossil fuels used in electricity, transportation, cooking sectors, and SBFs. Consideration of these would render much greater GHG savings. Similarly, for lack of appropriate data, the avoided particulate emissions due to coal, other petroleum fuels used in electricity generation and transportation, SBFs (cooking), and emissions from MSW burning were excluded. The inclusion of these would render better environmental performance of WTE schemes. This also requires a separate full LCA study.

In order to validate the results from this analysis, we have compared our results to those of other studies. This paper gives a lower value for India's total biomethane yields compared to Mittal *et al.*,²⁸ despite considering a wider variety of sectors and individual elements in each sector (*e.g.*, many more types of crops and industries). This may be attributable to the differences in data sources for production of crops and other products, the use of state-wise accessibility factors for crops and distinct experimental methane yields for all substances, which should represent the real-world scenario more closely. Moreover, our results are modest in that co-digestion can increase yields of biomethane, which has not been considered here, for reasons already mentioned in Section 2.1. The biomethane generation obtained in this paper is, however, much higher than the estimates of Rao *et al.*,²⁷ as we included more sectors and there has been an increase in production and consumption in the decade since Rao *et al.* was published.

Comparing individual sectors, we found that our calculated biomethane yields (and, consequently, the electricity generation potential) of animal wastes (excluding slaughterhouses) are similar, but lower than those found by Kaur *et al.*³⁰ (363 TWh from our calculations, as against 477 TWh). This difference is expected due to our detailed methodology, lower availability factors, and more recent data sources, as already explained in the Section 2.1.3.

This paper is the first study to quantify the achievable GHG abatement on using wastes as energy sources in India under



different end-use scenarios, so there are no published studies available to cross-validate the end-use-specific results.

The calculated GHG emissions from biomethane production per MJ, in Section 3.2 is found to be about 3 times that obtained by Singh *et al.*¹¹⁹ (10.5 gCO₂eq./MJ), due to the consideration of 3% biomethane leakage here, as opposed to 1% in the earlier study; these leakages constitute most of the emissions. The results on the final emissions of kerosene adapted from Garg *et al.*¹¹⁴ (169 gCO₂eq./MJ) agree well with those adapted from Singh *et al.*¹¹⁹ (171 gCO₂eq./MJ), but there is a small mismatch between the final emissions from LPG used in cooking as adapted from Garg *et al.*¹¹⁴ (130 gCO₂eq./MJ), and those from Singh *et al.*¹¹⁹ (160 gCO₂eq./MJ). We used adapted results from Garg *et al.*¹¹⁴ for both cases, to maintain consistency in the source. This also renders slightly more modest (and less optimistic) emission savings.

3.4. Comparisons with the state-of-the-art

The Indian Government has already launched the National Biogas and Manure management Programme (NBMM) and the National Project on Biogas Development (NPBD) to encourage electricity generation from biogas, and the generation of energy from municipal, industrial, and animal wastes.¹⁶⁴ However, India generated only 32 TWh of electricity from biofuels and wastes in 2019;¹⁴ *i.e.*, 4.3% of biomethane's estimated potential. India's annual biogas generation was 2.07 billion m³ in 2018–19;¹⁶⁵ less than 2% of the estimated potential. The total WTE installed capacity (including direct waste combustion for electricity) in India was 10.18 GW in 2021,¹⁶¹ which is roughly 12% of the annual potential estimated in this paper (a state-wise comparison is provided in Table 6). In 2018–19, the share of renewables (including hydro) in India's electricity generation was roughly 17%,³ which could be increased to 62% if all the waste-to-biomethane potential were harnessed. There was also negligible biofuel use in transportation in India in 2019.¹⁴ The transportation sector almost entirely uses fossil fuels, and the utilisation of biomethane could raise the share of renewables to 91% for the sector. These clearly denote the immense gap between the potential and the state-of-the-art in India and encourage policy formulations in favour of WTE generation.

3.5. Policy perspectives

This paper shows a clear incentive for investments and policies to support the conversion of wastes to biogas to reduce pollution and GHG emissions, given the potential, decentralised feedstock availability, and that biogas plants are economically viable and profitable in India.^{164,166} There is the added benefit of reducing dependency on imported energy (chiefly petroleum) and enhancing India's energy self-sufficiency. The social and economic costs of air pollution will also be eliminated.

WTE projects induce little or no encroachment upon agricultural lands (other than perhaps building some biogas plants); hence, the competition between growing crops for food and energy is largely avoided. The generation of biogas, which has an economic value, can also act as an incentive to collect,

segregate, and treat wastes. There is scope for providing more rural employment and ensuring grassroots development and innovation.¹⁶⁷ Allocating an economic value to wastes and setting up a market structure in which farmers can sell their crop residues and animal wastes, can generate additional income for farmers, while also preventing the open burning of these valuable energy resources. A country-wide economic assessment of biogas projects is needed to further highlight their economic potential.

There are several challenges for biogas projects: the high upfront investments,¹⁷ the timely availability and supply of appropriate feedstocks for mono or co-digestion for all biogas plants throughout the country, the efficient harvesting of crop wastes (especially with the lack of appropriate machinery with farmers), the lack of source segregation of MSW, and the considerable water requirements in biogas plants,^{168–170} are some major challenges. For electricity generation, the majority of existing power plants in the country use steam turbines for coal; while these can generate electricity from biomethane, the efficiencies are lower, at 40%.¹⁷¹ To exploit the higher efficiencies of CCGTs, these power plants will need retrofitting. A difficulty for the end uses as cooking and transportation fuels is that the domestic ovens and car engines of the masses will need technical modifications or replacements for using biomethane. Government policy support and large private investments are thus necessary. Furthermore, with the rising prices of petroleum products and cooking gas, the citizens might find it favourable to shift to using biomethane for their energy needs if it is cheaper and widely available.

A temporal assessment of waste availability (especially crop residues, which are seasonal and available only after harvests) is desired to design the biogas feedstock supply chains and plan storage effectively. For MSW, further investigation is needed into measures to incentivise and promote source segregation by citizens. The profits generated from biogas can encourage efficient MSW management, especially with the increase in organic content from 2005 levels (Section 2.1.4). To reduce fresh water demands, recirculating the liquid part of the digestate slurry after the solid portion has been removed (to be used as a fertiliser), can be helpful.⁴⁷ In some cases, wastewater and solid wastes are available together, and the water requirement can be readily met, *e.g.*, municipal solid wastes and wastewaters,¹⁷² or wastes in palm oil mills.¹⁷³

The findings of this study allude to some policy debates. The huge biomethane potential denotes the importance of considering biogas projects for renewable and sustainable energy generation on an equal footing with solar and wind power in India, especially noting that biomethane can generate firm electric power, which can complement the intermittent solar and wind sources (that solar and wind are given importance is evident from the greater corresponding targets and policy support¹⁷⁴). Also, biomethane provides greater flexibility for end-use and enables efficient waste management.

Presently, Indian policies encourage an increasing share of natural gas and LPG for transportation¹⁷⁵ and cooking;^{176,177} however, Fig. 3 shows that biomethane can save substantial quantities of GHGs compared to these. This raises the debate on whether natural gas and LPG should be encouraged as



transition fuels or at all, and whether undertaking large scale biogas projects could be a better move. Analysing the economics of countrywide biomethane projects will help to answer this, provide data on how replaceable the present-day fuels (especially cooking and transport) actually are, in terms of costs, and shed light on which of the three end-use scenarios discussed in this paper is more practical, despite biomethane-to-electricity giving the maximum GHG savings.

Our results raise another key question on whether heavily favouring electric vehicles (EVs) in India from 2030 onwards¹⁷⁸ will be good for GHG emissions and whether encouraging biofuels in transportation would be better, given the high share of coal in electricity generation (at present) and the increased electricity demands that this move will entail. Of course, generating electricity from renewables would help, but the relative energy efficiencies (of using biomethane directly as a transport fuel *versus* using electricity generated from biomethane and other renewables to power EVs) and economics need further research and consideration.

A major present-day policy supporting biogas is for family-sized biogas plants for clean cooking fuel provisions in rural areas.^{165,174} Installing large industrial biogas plants for this is a better alternative when considering biomethane yields, since it is difficult to maintain suitable temperature and pH conditions in family-sized biogas plants, thus leading to lower biogas yields. Many family-sized biogas plant users have reported lower yields in winters and unpredictability of fuel generation, which forced them to resort back to SBFs.^{17,26} Fig. 2 shows that nearly 26% of India's current cooking fuel demand is met by SBFs, coal and charcoal (electric cooking is only a meagre share of this¹⁷⁹), so, generating biomethane from the wastes that are currently used as SBFs would reduce indoor air pollution and concomitant health issues, in addition to reducing GHGs. The availability factor of wastes for biomethane generation would also increase, accompanied by a reduction in the felling of trees to procure fuelwood. So, there needs to be considerations on how to replace the SBFs^{180,181} (that are free) and kerosene (which can be purchased daily in small quantities¹⁸⁰) in rural areas with the comparatively (and potentially) expensive biogas generated industrially, without adversely affecting the poor populace and also preventing eventual fuel stacking¹⁷⁷ due to economic constraints.¹⁸⁰

The discussions in this paper show that the use of biomethane (from wastes) can help India in achieving six of the United Nations' (UN's) sustainable development goals: 'affordable and clean energy', 'climate action', 'sustainable cities and communities', 'good health and wellbeing', 'clean water and sanitation', and 'responsible consumption and production'.¹⁸²

4 Conclusions

This paper assesses and demonstrates the immense biomethane generation potential from all types of wastes produced in India. It creates a strong case for policy implementations that favour maximal biomethane generation and utilisation throughout the country. It includes all the states of India, involving every principal waste-producing sector, and is based on data published by the Government of India, reputable

international organisations, and results from the academic literature. The characteristics of biodegradable wastes from agriculture, horticulture, animal husbandry, and those generated in various Indian cities are also compiled.

This paper represents the most comprehensive evaluation of India's WTE potential to date, explores the possible displacement of unsustainable and polluting fuels with this biomethane under three end-use scenarios, and estimates the corresponding avoided GHG and PM emissions from such WTE conversion. It is found that more than 125 billion m³ of biomethane could be produced annually from waste resources in India, which would be able to supply around 47% of India's present electricity generation. This could be an important step towards sustainability, as biomethane leads to significant reductions in GHG emissions when compared with India's existing grid electricity. The annual avoided GHG emissions from the electricity sector would be 461 million tonnes of CO₂-equivalent (excluding the impacts of black carbon), accompanied by the removal of particulate emissions from fossil fuels and field burning of crop residues, appropriate waste management, reductions in air, water, and soil pollution, and improved energy access in remote areas.

Alternatively, the biomethane could be used to provide for all of India's cooking fuel needs (from only 43% of the generated methane) or 91% of India's fuel requirements for road transportation. The net avoided GHG emissions considering all the three end-use scenarios are between 284 and 461 million tonnes of CO₂ equivalent annually (excluding BC). The emission savings of PM_{2.5} and PM₁₀ combined, from the avoidance of FBCR alone, are between 1.8 and 2.1 million tonnes, and those of GHGs, between 37 million tonnes (excluding BC) and 101 million tonnes (including BC) of CO₂ equivalent.

This paper denotes ample scope for improvement from the present-day harness of biogas, as discussed with numeric evidences. There are some additional findings relating to the share of SBFs in cooking fuels, an increase of organic content in MSW over the past 17 years, and the comparisons of the present-day cooking and road transport fuels with biomethane in terms of carbon intensities. Some research areas and policy debates for the future are also explored.

Biomethane from wastes is a renewable and sustainable energy resource. Six sustainable development goals of the UN that can be achieved from waste-to-biomethane generation in India are identified, and the energy potential estimated in this paper is compared with the state-of-the-art, stressing the importance of the uptake of WTE schemes in India and the need for government policy support and private investments. This paper thus emphasises and highlights the importance of large-scale WTE conversion, which can be supported by the provided datasets on biomethane generation for energy pathway planners, policy makers, and environmental scientists.

Appendices

Appendix 1: Data compilations

Agriculture and horticulture wastes. Data for calculations involving agricultural and horticultural wastes are compiled in Table 8 below.





Table 8 Data for crop residues

Crop residue	Residue to product ratio (RPR)	Total solids content (TS, % of fresh matter)	Volatile solids content (VS _{TS} , % of TS)	Net volatile solids (VS, % of fresh matter)	Methane yield (BMP) Y _b for mono-digestion (m ³ per tonne-Vs)	References
Cereals						
Rice straw (physical and/or chemical pre-treatment with NaOH or Ca(OH) ₂ or Na ₂ CO ₃) ^a	1.5	85.56	82.05	70.2	277	29, 31, 51, 183–192
Rice husk	0.2	89.2	87	77.8	40 or 300 (used 300, because the higher yield was experimentally possible.)	29, 31, 46, 51, 184, 185, 193 and 194
Wheat straw and cobs (pre-treatment)	1.8	91.55	89.38	81.83	252	29, 31, 43, 183, 187, 195–203
Maize/corn stover	2.3	90.5	95.56	86.48	364	29, 54, 183, 196, 204–206
Millets (nutri-cereals, except maize)	1.55	91.48	94.43	86.38	293	29, 51, 54, 204, 207 and 208
Horticulture (except orchards)						
Aubergine/eggplant (brinjal)	0.18	19.4	94.1	18.26	374	206 and 209–211
Carrot leaves	0.45	14.8	83.6	12.37	312	194, 212 and 213
Potato	0.81	18.2	94.6	17.22	250	54, 214 and 215
Sweet potato	0.63	91.8	85.7	78.67	200.2	216 and 217
Tapioca/cassava	0.75	30.92	94.64	29.26	270.3	54, 218 and 219
Okra (pre-treated with NaOH)	0.4	15.15	47.87	7.25	369.09	220
Tomato	0.44	10.25	78.24	8.02	240	205, 210, 215 and 221
Onion	0.4	28.55	90.68	25.89	353	215
Cauliflower	1.49	5.69	90.16	5.13	250	55, 222 and 223
Cabbage	1.49	6.7	92.3	6.18	223.88	55, 214, 222 and 223
Coriander	1.15	11.19	85.7	9.59	309	54, 209 and 223
Beans	1.6	10			128 (m ³ per tonne-waste; not VS)	216 and 224
Cucumber	0.2	10.77	74.7	8.05	280	210, 212 and 221
Radish	0.45	5.76	90.1	5.19	272	212, 213 and 225
Capsicum	0.45	20.35	80.64	16.41	120.6	210, 212 and 213
Chilli	1.5	92.987	85.37	79.38	104.2	210 and 226
Ginger	1.15	90	83.88	75.49	195 ^b	212 and 213
Pea	1.1	90	83.88	75.49	195 ^b	206 and 212
Banana pseudostems and leaves (cutting and chopping)	3	4.82	78.42	3.78	347	55 and 227–229
Turmeric	0.3 (ginger)	90	83.88	75.49	195 ^b	212 and 213
Cumin	1.55	10	83.88	8.39	195 ^b	212
Cardamom	0.64	90	83.88	75.49	195 ^b	212
Garlic	0.2	10	83.88	8.39	195 ^b	212
Melons (watermelon and muskmelon)	0.2	20	83.88	16.78	195 ^b	212
Areca nut frond ^c	3 ^e t ha ^{−1}	59.46	78.3	46.56	200	29 and 54
Areca nut husks	0.8	91.12	79.87	72.78	91.12	29, 54, 230 and 231
Coconut frond ^c	4 ^e t ha ^{−1}	59.46	78.3	46.56	200	29 and 54
Coconut husk	0.53	86.96	27.82	24.19	Not used	29, 54 and 232



Table 8 (Contd.)

Crop residue	Residue to product ratio (RPR)	Total solids content (TS, % of fresh matter)	Volatile solids content (VS _{TS} , % of TS)	Net volatile solids (VS, % of fresh matter)	Methane yield (BMP) Y _b for mono-digestion (m ³ per tonne-VS)	References
Cash crops and plantation crops (availability factor for 'others'²⁵)						
Tobacco	2.95	92.86	93.79	87.09	175 without treatment, 312 (7% AHP treated, used here)	50 and 233
Tea	1.2	90.5	92	83.26	217	233–235
Coffee (pruning residues)	See Table 9	91.3	82.15	75	109 (from orchard pruning wastes section)	236 and 237
Sugarcane tops and leaves (alkaline pre-treatment will improve)	0.13	76.7	86.3	66.19	228.33 (mean)	206, 233 and 238
Sugarcane bagasse (alkaline pre-treatment will improve)	0.3	55.4	96	53.18	281 (mean)	206, 233 and 238
(considered 80% sugarcane for this, corresponding to sugar production)						
Sugarcane press mud	0.036	27.7	80.8	22.38	198	239 and 240
Cotton stalk, boll shell, husks	3.8 ^c t ha ^{−1} , 1.1, 1.1, respectively	85.57	94.72	81.05	148.74	29, 216 and 241
Jute stalk	2	91.41	94.78	86.64	193 ^d	29, 242 and 243
Cocoa	1.5			13	193	78 and 244
Oilseeds and palm oil						
Mustard and rapeseed	1.8	87.97	89.05	78.34	132.3	29 and 49
Sunflower stalk	3	94	93.61	88	192	29 and 245
Safflower stalk	3	94	93.61	87.99	89	29 and 246
Soybean	1.7	87.5	91	79.63	196	29, 194 and 247
Palm oil empty fruit bunches (EFB)	0.22	43.6	89.91	39.2	358	112, 173 and 248–251
Oil palm fronds	0.55	59.46	78.3	46.56	200	252–255
Pulses (straws)^d						
Gram	1.1	65	88.77	57.7	279.2	29, 242 and 256
Lentil	1.8	65	88.77	57.7	279.2	29, 242 and 256
Tur/Arhar	2.5	65	88.77	57.7	279.2	29, 242 and 256

^a Physical pre-treatment (cutting and chopping/pulverisation, heating, or microwave) and/or chemical (alkaline) pre-treatment improves biomethane yields.^{30,165,183,187,238,257–259} The cases for chemical pre-treatment, which unmasks lignin and improves methane yields, are indicated in this table; physical pre-treatments like chopping and cutting is expected for most wastes. However, heat, ultrasound, and microwave treatment would incur energy expenditure and as such, were not included in this study.^b Calculated using the basic formula as experimental results were not found.^c The results on TS, VS, and BMP for oil palm fronds were reused for coconut and arecanut fronds.^d The results for lentils were used for all other pulses in the absence of specific data.^e The RPRs for arecanut fronds, coconut fronds, and cotton stalks are not pure ratios, but are expressed in t ha^{−1} (tonnes per hectare) of wastes generated.

Table 9 Data for orchard pruning residues (biomethane generation = 109 m³ per tonne-FM (fresh matter))^e

Fruit/nut	Pruning wastes (tonne per hectare) ⁶²	RPR (calculated)
Almond	3	2.65
Aonla (Amla)	3.8 ^a	0.33
Apple	3.5	0.43
Grapes	4.5	0.21
Guava	3.8 ^a	0.25
Lime and lemon	2.1	0.21
Mango	3.8 ^a	0.42
Orange	2.1	0.19
Papaya	2.1 ^b	0.05
Pineapple	3.8 ^a	0.22
Pomegranate	3.8 ^a	0.32
Sapota/sapodilla	3.8 ^a	0.31
Strawberry	3.8 ^a	0.5
Sweet orange	2.1	0.13
Walnut	3	1.15
Cashew	3	3.9
Tamarind	3.8 ^a	0.91
Olives ^c	1.8	NR
Peach ^c	6	NR
Pear ^c	8	NR
Cherry ^c	4	NR
Apricot ^c	5.5	NR
Hazelnut ^c	3	NR
Coffee (not used to obtain mean ^d)	17 (ref. 260)	NR
Mean	3.8	NR

^a Mean value. ^b Used the lowest value instead of the mean, as papaya plants are not expected to produce as much pruning residues as larger trees like mango and others, based on the authors' observations. ^c NR = Not required. These are not required as the fruits are not grown in India in appreciable quantities and hence not reported in the horticultural statistics; these are hence also not included in our assessment. The data were used only to obtain a mean value. ^d Coffee shrubs are usually smaller than the other fruit trees. ^e Note: Banana is included as a horticultural product in the previous Table 8.

Orchard pruning wastes. Data for calculations involving orchard pruning wastes are compiled in Table 9 below.

Animal wastes. Data for calculations involving animal wastes are compiled in Table 10 below.

India's municipal solid wastes. Data on the characteristics of MSW in India are compiled in Table 11 below.

Appendix 2

The IPCC default methodology for estimation of methane emissions from MSW is based on the following basic equation:^{121,159,160,310}

$$\text{MCH}_4 = (\text{MSW}_T \times \text{MSW}_F) \times \text{MCF} \times \text{DOC} \times \text{DOC}_F \times F \times \{(16/12) - R\} \times (1 - \text{OX}) \times (\text{CF}) \quad (5)$$

Here, MCH₄ is the annual methane emission from India's MSW (in tonne per year). MSW_T is the total quantity of MSW generated in India. MSW_F is the fraction of MSW disposed of

Table 10 Data for animal wastes

Species	Mean live weight (kg)	Wastes per animal per day (% of body weight)	Availability (%)	Total solids (TS) as a % of fresh matter	Volatile solids (VS) as a % of fresh matter	Biochemical methane potential (BMP, m ³ per tonne-FM)	References
Cattle	336	6	70	18.67	14.33	29	30, 43, 50, 53, 84, 205 and 261–263
Buffalo ^a	440	6	70	18.67	14.33	29	30, 43, 50, 53, 84, 205 and 261–263
Yak and mithun ^b	440	6	50	18.67	14.33	29	
Goat	34	4	13	59.22	47.55	73	30, 37, 73, 74, 76, 81–84 and 262–265
Sheep	31	4	13	34.51	29.465	63	30, 37, 73, 74, 76, 81–83 and 261–265
Pig	80	4	80	27.8	22.89	82	50, 261 and 262
Horse	268	6 (same as cattle)	50	29.79	25.77	52	84, 262, 264 and 266
Donkey (same as horse, except live weight)	160	6	50	29.79	25.77	52	262, 264, 266–268
Mules (same as horse)	268	6	50	29.79	25.77	52	262, 264 and 266–268
Camel	570	6 (same as cattle)	50	36	21.57	35.8	84, 263, 269 and 270
Poultry	1.5 (for manures) – 1.7 (for slaughterhouse)	3	90	49.16	37.27	109	30, 37, 43, 50, 71–74, 76, 86, 261, 262 and 271

^a Same parameters as cattle, other than live weight. ^b Same parameters as buffalo.



Table 11 Characteristics of MSW in Indian cities

City	State/UT	Biodegradable fraction (except paper and textile)	TS (%)	VS (% of total wastes)	References
Agartala	Tripura	55.43	63.69	NR	272
Agra	Uttar Pradesh	46.38	72	NR	11, 87, 88 and 273
Ahmedabad	Gujarat	44	68	NR	11, 87, 88, 274 and 275
Aizwal	Mizoram	49	57	NR	88 and 276
Allahabad	Uttar Pradesh	45.3	74.14	NR	277
Amritsar	Punjab	65.05	39	NR	11 and 88
Asansol	West Bengal	47.24	56	NR	88 and 278
Bangalore	Karnataka	81.96	45	NR	16 and 88
Bhopal	Madhya Pradesh	69	NR	46.6	279
Bhubaneswar	Odisha	49.81	41	NR	88
Chandigarh	Chandigarh	52	54.22	NR	280 and 281
Chennai	Tamil Nadu	55	45	50	172 and 282
Coimbatore	Tamil Nadu	63.24	43	NR	11, 87, 88 and 283
Cuttack	Odisha	50	30	NR	284
Daman	Daman and Diu	29.6	47	NR	88
Delhi	Delhi	73	59.4	28.2	95 and 285–287
Dehradun	Uttarakhand	80	40	NR	88 and 288
Dhanbad	Jharkhand	75	51.6	NR	289
Faridabad	Haryana	42	66	NR	11, 88 and 290
Gandhinagar	Gujarat	34.3	76	NR	88
Gangtok	Sikkim	52.5	66	NR	88 and 276
Guwahati	Assam	45.1	80	NR	88, 276 and 291
Gwalior	Madhya Pradesh	55.2	48.96	NR	292
Hardwar	Uttarakhand	49.1	85.74	NR	293
Hyderabad	Telangana	69.9	54	NR	87, 88 and 294
Imphal	Manipur	53.28	60	NR	88 and 276
Indore	Madhya Pradesh	43	15	88.5	88, 90 and 295
Itanagar	Arunachal Pradesh	53.81	50	NR	88 and 276
Jabalpur	Madhya Pradesh	58.07	65	NR	11, 87 and 88
Jaipur	Rajasthan	45	60	NR	87, 88 and 280
Jalandhar	Punjab	37	70	20.4	296
Jamshedpur	Jharkhand	64	69	NR	11, 87 and 88
Jorhat	Assam	57.1	54.91	NR	88 and 276
Kanpur	Uttar Pradesh	27	54	NR	11, 87, 88 and 297
Karavatti	Lakshadweep	46.01	75	NR	88
Kochi	Kerala		58.39	19.63	88 and 291
Kolkata	West Bengal	79.8	50	NR	122 and 298
Kohima	Nagaland	55.1	54	NR	11, 87 and 88
Lucknow	Uttar Pradesh	54.86	35	NR	87, 88 and 299
Ludhiana	Punjab	40	40	NR	11, 87 and 88
Madurai	Tamil Nadu	49.8	35	NR	11, 87 and 88
Meerut	Uttar Pradesh	55.32	54	NR	11, 87 and 88
Mumbai	Maharashtra	54.54	68	NR	87, 88, 300 and 301
Nagpur	Maharashtra	42	46	NR	11, 87, 88 and 291
Nainital	Uttarakhand	77.2	59	NR	88 and 276
Nashik	Maharashtra	52.76	0	NR	11, 87, 88 and 302
Panjim	Goa	81.6	38	NR	88
Patna	Bihar	53.95	53	NR	87, 88, 94 and 303
Pimpri-chinchwad	Maharashtra	54.32	64	NR	87 and 304
Port Blair	Andaman and Nicobar	32	52	NR	88
Puducherry	Puducherry	48.25	37	NR	280
Pune	Maharashtra	50	46	NR	305
Raipur	Chhattisgarh	69.3	70.28	62.61	11, 87 and 88
Rajkot	Gujarat	51.4	71	NR	11, 87 and 88
Ranchi	Bihar	41.5	83	NR	11, 87 and 88
Roorkee	Uttarakhand	51.49	51	NR	306
Sangamner	Maharashtra	39.53	86.57	NR	307
Shillong	Meghalaya	42.22	61.5	NR	88 and 276
Silvassa	Dadra and Nagar Haveli	62.54	37	NR	88
Simla	Himachal Pradesh	71.67	58	NR	88 and 276
Srinagar	Jammu and Kashmir	53.01	40	NR	87, 88 and 308
Surat	Gujarat	54.65	39	NR	11, 87 and 88
Thane	Maharashtra	56.87	49	NR	11, 87 and 88
Tiruvananthapuram	Kerala	42	49	NR	88



Table 11 (Contd.)

City	State/UT	Biodegradable fraction (except paper and textile)	TS (%)	VS (% of total wastes)	References
Tura	Meghalaya	72.96	40	NR	87 and 88
Vadodara	Gujarat	54.86	37	NR	88 and 309
Varanasi	Uttar Pradesh	60.47	52	NR	287
Vijayawada	Andhra Pradesh	46.13	65.28	NR	11, 87 and 88
Visakhapatnam	Andhra Pradesh	59.43	54	NR	11, 87 and 88
Mean values		53.93	54.51		

Table 12 Data for DOC calculations

City	Paper, cardboard, textile (A)	Garden, park, other (B)	Food waste (C)	Wood (D)	DOC (calculated)	References
Agartala	10		55.43		0.1231	272
Agra	1.5	8	37	4.6	0.0889	273
Ahmedabad	3	4	40		0.0788	274 and 275
Aizwal	9.4		49		0.1111	276
Allahabad	6.91		45.3		0.0956	277
Asansol	9.59	32.25	8	6.99	0.1262	278
Bangalore	12.61		72		0.1584	16
Bhopal	12.06	22.15	43.18	0.5	0.1522	279
Chandigarh	7.7		52		0.1088	280 and 281
Chennai	15	26	15	14	0.1687	282
Coimbatore	11.225	3.827	56.505	1.924	0.1419	283
Cuttack	3	1	49		0.0872	284
Delhi	17.93	15.83	56.3		0.1831	285
Dehradun	8		80		0.152	288
Dhanbad	3		75		0.1245	289
Faridabad	7.16		42		0.0916	290
Gangtok	10		52.5		0.1188	276
Guwahati	21.35	5.25	37.4	2.45	0.1578	291
Gwalior	13.8		55.2	2.54	0.1456	292
Haridwar	4.5	27.325	21.77		0.0971	293
Hyderabad	17.4	23	37.3	1.1	0.168	294
Imphal	6.72		53.28		0.1068	276
Indore	7		43		0.0925	295
Itanagar	8.39		53.81		0.1143	276
Jaipur	8		45		0.0995	280
Jalandhar	15.5		35	2	0.1205	296
Jorhat	6.4		57.1		0.1113	276
Kanpur	3		12	14	0.072	297
Kochi	4.9		79.8		0.1393	291
Kolkata	8	5	45.5	1.2	0.1124	122 and 298
Kohima	7.64		54.86		0.1129	276
Lucknow	6.4		40		0.0856	299
Mumbai	21.8	6.3	35.7		0.1515	300 and 301
Nagpur	9.6		77.2		0.1542	291
Nainital	11.74		52.76		0.1261	276
Nashik	6.8	24.5	54	3.1	0.1592	302
Panjim	0.92	1.31	52.6	0.04	0.0849	94
Patna	4.58	7.735	45.94	0.645	0.1023	303
Pimpri-chinchwad	12.17		33.5	11.03	0.132	304
Puducherry	15		50		0.135	280
Pune	14.7		69.3		0.1628	305
Roorkee	12.78	22.5	17.03		0.1149	306
Sangamner	8.6	12.22	20.5	9.5	0.1144	307
Shillong	9.46		62.54		0.1317	276
Simla	7.99		53.01		0.1115	276
Srinagar	5.77	3.7	49.7	1.25	0.1077	308
Tura	8.64		54.86		0.1169	276
Vadodara	7.39	0.4	60.07		0.1203	309
Varanasi	12.54		46.13		0.1194	287



in open dumps, which has been considered to be 80% of the wastes produced in the urban areas (as published papers suggest that this value is between 72% and 90%^{11,15}). MCF is the methane correction factor, whose value is 0.5 for landfills and 0.25 for open dumpsites;¹²³ the latter is useful for our paper. DOC is the degradable organic carbon; its value can be estimated if the composition of wastes is roughly known (eqn (6)). DOC_F is the fraction of organic carbon undergoing decomposition to yield methane, the value of which, has been suggested to be 0.77 for India's countrywide estimate (for a temperature of 35 °C).^{159,160} R is the volume of recovered landfill gas, which is zero for the present case, as landfill gas as an energy source is not being considered here (and such capture is not prevalent in India¹⁵⁹), and the gas is assumed to escape into the atmosphere. OX is the oxidation factor, with a default value of zero. The term CF denotes a correction factor introduced by us to provide more realistic estimates of the methane emissions from landfills and avoid overly optimistic estimates of the displaced GHG emissions of biogas production and use. Multiple field studies^{160,311–313} suggest that the actual methane emissions from a landfill are 2 to 7 times lower than the value estimated by the IPCC default methodology. So, in order to ensure that the results of this analysis are conservative, the value of CF has been assumed to be (1/4.5). This correction factor brings the estimated values of methane emissions close to the results of the first order decay method, as can be observed from the results of Ghosh *et al.*¹⁶⁰, and prevent an overly optimistic result.

$$DOC = (0.4 \times A) + (0.17 \times B) + (0.15 \times C) + (0.3 \times D) \quad (6)$$

Here, A = fraction of wastes like textile, paper, and cardboard, B = fraction of organic wastes from gardens, parks, road sweepings, and other sources, except food. C = fraction of biodegradable food wastes. D = fraction of wood wastes.

To calculate DOC, data from the literature on waste compositions in multiple Indian cities were used (compiled in Table 12). In some cases, the classification of the wastes was not exactly as described above. In cases where only 'biodegradable wastes' or 'compostable wastes' was mentioned, this entire fraction was categorised under food wastes. This is a potential source of error as some wood or garden wastes may get included in food wastes. However, this is not a major reason for concern as this was only for very few cases among 49 cities. Moreover, the coefficients of B , and C are not very different, hence the introduced error will be small. Paper and textiles were always found to be reported separately. The data are summarised in Table 12. Finally, the mean value of DOC was calculated ($=0.1224$) for India, which was then used to obtain the total methane emissions ($=4.49$ million tonnes of CO_2 -equivalent; 20.21 million tonnes without using our introduced correction factor).

There are other sources of error in this calculation. First, the generation of methane from wastes depends on the ambient temperature (and rainfall, which decides the moisture in the wastes), the impacts of which have not been accounted for. The temperature of 35 °C, though reasonable for most of India in

summer, is not a good assumption for mountainous areas and will lead to overestimations in winters and monsoons. The impact of rainfall, though not explicitly applicable in the IPCC default method, appears as a factor in the LANDGEM procedure,¹²² which has not been used here. This is because the chief aim of the present paper is not to calculate methane emissions from MSW with high accuracy but to only obtain an approximate estimate of the avoided GHG emissions. Estimating the methane emissions from MSW for the whole country requires separate considerations of the various climatic zones in India, and the seasonal variations of the compositions of wastes in various cities. We suggest this as a separate study.

The correction factor introduced by us is another source of error, as its exact value cannot be ascertained and could depend on the age of the garbage dump being considered.^{160,313} The default methodology assumes that the same amounts of wastes are deposited yearly in the dumps and that methane emissions are constant every year.¹⁵⁹ It is independent of the age of the dump, which is not ideal, but is well suited to our study since we deal with waste quantities in the entire country and not individual dumps or cities. This was corrected for by the stated correction factor.

Another source of uncertainty is the assumption that 80% of the wastes generated are disposed of in open dumpsites. However, there are no better ways of accurately quantifying this and the present assumption is expected to yield a reasonably good estimate, based on literature review. In Singh *et al.*,¹⁵⁹ 70% of the wastes generated in India have been assumed to be landfilled. From literature survey,^{10,11,15,160} 80% open dumping seems more plausible. Despite these uncertainties, the eqn (5) and (6) are expected to give a useable estimate of methane generation from open municipal dumpsites in India as it is based on a dependable IPCC methodology and a comprehensive literature review.

Abbreviations and acronyms

AD	Anaerobic digestion
AF	Accessibility/availability factor
BC	Black carbon
BMP	Biochemical methane potential
CCGT	Combined cycle gas turbine
CNG	Compressed natural gas
CPCB	Central Pollution Control Board
EF(s)	Emission factor(s)
EV(s)	Electric vehicle(s)
FAO	Food and Agriculture Organisation of the United Nations
FBCR	Field burning of crop residues
FM	Fresh matter
GHG(s)	Greenhouse gas(es)
GWP	Global warming potential
HRT	Hydraulic retention time
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment



LCV	Lower calorific value
LPG	Liquified petroleum gas
MSW	Municipal solid wastes
PM	Particulate matter
PNG	Piped natural gas
RCR	Residue-to-crop ratio
RPR	Residue-to-product ratio
SBF(s)	Solid biomass fuel(s)
SRP	Surplus residue production
TRP	Total residue production
TS	Total solids (content)
VS	Volatile solids (content)
WTE	Waste-to-energy
kWh	Kilowatt-hours
TWh	Terawatt-hours

Author contributions

Dey: conceptualisation, methodology, validation, formal analysis, investigation, writing – original draft, visualisation, funding acquisition. Thomson: conceptualisation, writing – review & editing, supervision.

Conflicts of interest

There are no conflicts to declare.

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