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ORIGINAL ARTICLE

Emission profile of waste sector in Pakistan

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Abstract

Substantial increase in greenhouse gas (GHG) emissions from waste sector by rapid population growth and urbanization, emphasizes on the need for mitigation actions to meet commitments of the Paris Agreement (PA). The sector emitting high methane (CH_4) emissions has potential to meet emission reduction targets. Detailed segregated information of waste-related activities responsible for emissions is highly needed for accurate estimation of emissions and placing mitigation actions thereafter. The present study aims to provide an in-depth analysis of all such source activities with associated emissions in one place, needed for tracking progress on waste sector since country's nationally determined contributions (NDCs) submission and exploring opportunities for mitigation actions. In this study, emission estimations for 2019–2020 were carried out in accordance with Intergovernmental Panel on Climate Change (IPCC) revised 1996 guidelines for national GHG inventories. The results showed that waste sector emitted 26.94 million tons of carbon dioxide equivalent ($MtCO_2e$) emissions in the inventory year, of which 23.88 Mt were CH_4, 2.67 Mt were nitrous oxide (N_2O) and 0.39 Mt were CO_2 emissions. Solid waste disposal (SWD) with 14.30 (53.1%) $MtCO_2e$ emissions was the major emitting category, followed by wastewater handling and discharge (11.43 Mt; 42.4%) and waste incineration and open burning (1.21Mt; 4.5%). Given the highest share of solid waste to the total GHG emissions from waste sector, the results of this study suggest to focus on solid waste more seriously. Further, the current scenario of waste generation, collection and disposal stresses on improved waste management practices providing reliable data that can feed into waste management strategy and GHGs mitigation.

Keywords Greenhouse gas emissions · Solid waste · Wastewater · Waste incineration · Open burning

Introduction

Anthropogenic greenhouse gas (GHG) emissions are main drivers of climate change, controlling or reducing their concentration in the atmosphere is most pressing challenge of the today's world [1]. This linkage between rising global temperatures and GHGs concentration in the atmosphere, has been established true throughout the Earth's history [2]. A comparative analysis of global average temperature with that of from 1961 to 1990 shows that global temperatures have sharply increased to about 0.7 °C higher than those of historical baseline, 1961–1990. Further back analysis to 1850 shows temperatures 0.4 °C colder as compared to those of baseline, amounting an average increase of 1.1 °C [3].

Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report has established the link of this warming since 1850 with increasing concentration of GHG emissions in the atmosphere. Since the pre-industrial time, the concentration of anthropogenic GHG emissions has increased unprecedentedly over last 800,000 years, resulting as a dominant cause of global warming since mid-twentieth century [4]. To address this cause of global warming, climate actions are needed to stabilize or reduce GHGs concentration in the Earth's atmosphere [1]. The efforts in this regard have matured in the form of a global agreement at the twenty-first session of the Conference of the Parties (COP 21) in Paris, called as The Paris Agreement (PA). The PA is legally binding international treaty on climate change adopted by 196 Parties (Countries) under United Nations Convention on Climate Change (UNFCCC). The PA 2050 Agenda for net zero global carbon emissions around mid-century to meet the 1.5 °C global warming target, urges the member states to take action to mitigate climate change and adapt to its

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impacts. Climate crisis is disrupting national economies and affecting lives everywhere. The recent endorsement of 2020 as one of the warmest years on historical record by the World Meteorological Organization is a blunt reminder of the persistent pace of climate change, which is devastating lives and livelihoods across the globe [5]. Due to the interlinked nature, achieving PA's goal of addressing the climate crisis, heavily relies on reducing global concentration of GHGs. The urgent action for saving lives and livelihoods is necessary to address the climate emergency.

The first step in this regard is global stocktaking of GHG emissions from source sectors of economy and commitments with proposed actions to reduce these emissions. The global stock of GHGs shows that emissions excluding emissions from land-use change and forestry (LUCF) have increased from 46,730.3 million tons of carbon dioxide equivalent ($MtCO_2e$) to 47,515.3 $MtCO_2e$ from 2017 to 2018. The sectoral share in global total of 2017 emissions, 49,947.4 $MtCO_2e$ (including LUCF) includes 36,435.64 (73%) $MtCO_2e$ from energy sector, 5884.97 (12%) $MtCO_2e$ from agriculture, 3217.07 (6.4%) $MtCO_2e$ from land-use change and forestry sector, 2825.88 (5.7%) $MtCO_2e$ from industrial processes and 1583.86 (3.2%) $MtCO_2e$ from waste sector [6]. In 2019's global fossil fuel emissions of 36,700 $MtCO_2$, the Asia–Pacific regional share is 17,600 Mt accounting for nearly half of the global total [7]. It is, therefore, obvious that the Asia–Pacific countries including Pakistan can play a crucial role in achieving GHG reduction goals, for which accurate estimation of GHG emissions from all responsible sectors of economy is a pre-requisite.

Pakistan's reported emissions in nationally determined contributions (NDCs) to UNFCCC are 405.07 $MtCO_2e$ for the year 2014–2015, of which 185.97 (45.9%) Mt are from energy, 174.56 (43.1%) Mt from agriculture, 21.85 (5.4%) Mt from industrial processes, 12.29 (3%) Mt from waste and 10.39 (2.6%) Mt are from LUCF sector [8]. Pakistan, although minor emission contributor in the region, aims to strengthen the global response to the threat of climate change under PA by reducing its emissions from all sectors of economy. Pakistan's NDCs define its efforts to reduce emissions and adapt to the impacts of climate change. To submit the updated NDCs and communicate the updates every 5 years, representing a progression compared to the previous NDC and reflect its highest possible ambition, a detailed national GHG inventory has become a cornerstone of the Pakistan's reporting obligations to the NDCs. It is also essential for understanding development trends, improving resource management and energy efficiency and developing policies to address climate change issues. For this, accurate and precise estimation of emissions from all source sectors as per prescribed IPCC guidelines for the preparation of national GHG inventories is necessary.

At present, waste sector is the neglected one in this regard. According to recent estimates, Pakistan is generating about 30 million metric tons of municipal solid waste (MSW) annually. Furthermore, a significant increase is expected in future due to rapid population growth, urbanization and economic development under China–Pakistan Economic Corridor [9]. About 60% of this generated waste is collected, of which 80% is in larger cities and nominal in most rural areas [10]. As for waste disposal is concerned, managed landfills are practically nonexistent. Therefore, urban waste is typically left uncollected (40%) or dumped on open grounds (60%). Moreover, the available published information on source and emission data from waste sector is scattered and presents surface analysis of the sector only. This information gap requires research progression on waste sector and its inclusion in the updated/ambitious NDCs as one of the emission contributing sectors which has the potential to help the country meet its emission reduction commitments, especially since waste sector gives rise to methane (CH_4) emissions, with high global warming potential. Therefore, an in-depth analysis of waste sector on lines of agriculture sector [11] is required to address issues related to activity data and associated emissions, thereby providing a baseline for waste sector in the updated NDCs.

This study will provide a detailed analysis of all source activities in waste sector responsible for emissions including data-sets, assumptions and GHG calculations in accordance with IPCC guidelines. Therefore, the study aims to i) provide most recent emission profile of waste sector for tracking progress on it since country's first NDCs submission; ii) provide a baseline for waste sector in revising/updating country's ambitious NDCs; and iii) provide consolidated scientific information in one place for national reporting and further studies on waste sector in Pakistan.

Methodology

In this study, GHG inventory of waste sector for the year 2019–2020 have been compiled in accordance with IPCC revised 1996 guidelines for national GHG inventories (hereinafter referred to as IPCC 1996 guidelines). The IPCC prescribed methodology is based on three tiers/levels of details, Tier 1, Tier 2 and Tier 3. Tier 1 employs the most basic information on activity data and emission and removal factors. It provides guidance to use default information provided in IPCC guidelines, therefore, it is also called as default method. Tier 2 estimation method is similar to that of Tier 1 but demands country specific data on emission/removal factors and source activities. Tier 3 is a data rigorous estimation method, therefore, known as the most complex one. It is usually based on model outputs and high resolution satellite data for LUCF sector [12].

In the compilation of this GHG inventory, Tier 1 method has been employed using default emission factors matching country's national circumstances. The default emission and other factors are mostly regional defaults for Asian, South Asian or Indian Subcontinent provided in IPCC 1996 guidelines. The basic tier is used because of its less data intensive applicability which ensures availability of complete reliable data at national level required for precise and accurate GHG inventory compilations. It is the quality of data that actually makes any tier method accurate, if data is of low quality then it can worsen the accuracy of higher tier methods [12]. This is the reason for preferring Tier 1 method over any of the higher tiers.

All categories of waste sector responsible for GHG emissions in Pakistan are considered in this GHG inventory compilation, detail of which is as follows.

Waste emission categories

Waste sector is responsible for the emissions of three important GHGs including CO_2 CH_4 and nitrous oxide (N_2O). The responsible source categories for these emissions include:

- Solid waste disposal sites (SWDS)
- Waste incineration and open burning
- Wastewater handling and discharge
- Human sewage

The source data, assumptions and estimation methods used for emissions estimation from each of the source categories is provided below.

Solid waste disposal sites

SWDS are responsible for CH_4 emissions when organic/degradable component in the disposed-off solid waste in these sites decomposes anaerobically (in the absence of oxygen). The SWDS provide an anaerobic environment which favors continuous waste decomposition at a diminishing rate for many years to completely decomposed [13]. Some of the most common plastics in solid wastes have recently been reported to release CH_4 and ethylene when exposed to sunlight [14]. The IPCC guidelines provide guidance on two methods to estimate CH_4 emissions from SWDS including Tier 1 method, the default one and Tier-2 known as first order decay method. The default method being based on the assumption of emitting all potential CH_4 emissions in the same year in which waste is deposited, produces reliable and actual annual emissions, provided the amount and composition of deposited waste has been constant over years [13].

In view of the constant amount and composition of the waste deposited at SWDS over the years and availability of the reliable waste generation and disposal data on annual basis, the IPCC default method has been used in these emission estimates.

Data and assumptions In Pakistan, MSW and some part of industrial solid waste (ISW) are disposed to SWDS. Annual amount of 18.4 Mt of MSW generated from urban population [15] in the inventory year is calculated on the basis of MSW generation rate of 0.65 kg/capita/day [16] and 60% of which (i.e., 11.02 Mt) is assumed to be disposed to SWDS [17], 25% is openly burnt, 3.54% is incinerated in incinerators and remaining 11.5% is openly spread. The composition data of MSW for food waste, paper waste, wood waste, textile waste and other waste are IPCC regional defaults [12] except garden waste [18] and nappies [19] which are based on national statistics.

There are about 400+ operational industrial units in Hattar Industrial Estate of Pakistan which produce around 0.004 Mt of ISW annually at the rate of 0.000011 Mt (11,000 kg) per day [20], of which 65% is sold to local contractors, 25% is dumped in nearby SWDS and 10% is burnt. The degradable fraction of this 25% dumped waste in the SWDS is assumed to be responsible for CH_4 emissions and is considered in this GHG inventory [20]. Degradable ISW of 0.00094 Mt is disposed to SWDS comprising food waste (including 10% ghee, 2% sugar, 2% floor and 1% expired food), cardboard waste (including 15% packing material and 4% cardboard), and textile waste (10% yarn and 5% jute bags) [20].

Methodological equation The estimation of CH_4 emissions from SWDS is carried out using the following equation:

$$\text{Emissions}_{\text{CH4}} = \left[\left(\text{MSW}_\text{T} \times \text{MSW}_\text{F} \times L_0\right) - R\right] \times (1 - \text{OX}), \tag{1}$$

where $\text{Emission}_{\text{CH4}}$ is the total CH_4 emissions ($GgCH_4$/year), MSW_T is the total MSW generated (Gg/year), MSW_F is the fraction of MSW disposed at SWDS, L_0 is the methane generation potential [MCF·DOC·DOCF·F·16/12 (Gg CH_4/Gg waste)], MCF is the methane correction factor (fraction), DOC is the degradable organic carbon [fraction (Gg C/Gg MSW)], DOC_F is the fraction DOC dissimilated, F is the fraction by volume of CH_4 in landfill gas, R is the recovered CH_4 (Gg/yr), OX is the oxidation factor (fraction).

Waste incineration and open burning

Waste incineration is the combustion of all types of waste (i.e., solid and liquid waste) in incinerators under controlled conditions. Types of waste including MSW, clinical waste, industrial waste, hazardous waste and sewage sludge are incinerated but with varying amount in different regions of the world. The incineration of MSW is more commonly practiced in developed countries, while in developing countries clinical and hazardous wastes are mostly incinerated [12].

Open burning is the open-air burning of combustible waste particles of different types of waste including wood, paper, plastics, rubber, textiles, oils and other debris in open dumping sites resulting in direct release of emissions in the atmosphere. This type of management practice is mostly practiced in developing countries [12].

Both types of waste management practices (i.e., waste incineration and open burning) are responsible for CO_2, CH_4 and N_2O emissions. Normally, CO_2 emissions are more significant as compared to CH_4 and N_2O emissions [12], 12.

Data and assumptions In Pakistan, varying amounts of four types of waste including MSW, industrial, hazardous and clinical waste are assumed to be incinerated for this GHG inventory compilation.

The incineration practice of MSW is mostly followed in developed countries or developed cities of developing countries [12]. Therefore, nine major cities of Pakistan including Karachi, Hyderabad, Lahore, Rawalpindi, Gujranwala, Sialkot, Faisalabad, Multan and Bahawalpur, where waste management companies are working, are considered for this type of waste management practice. For the inventory year, annual amount of 6.51 Mt of MSW generated by the population [21] of these cities is calculated on the basis of MSW generation rate of 0.65 kg/capita/day [16] and 10% of which (i.e., 0.65 Mt which is 3.54% of total MSW produced) is assumed to be disposed to SWDS. In case of industrial waste of 0.004 Mt produced in the inventory year, 10% of waste (0.0004 Mt) is assumed to be incinerated [20]. While, of hazardous waste of 0.9093 Mt produced in the inventory year, 70% is treated in sanitary landfills, 10% (0.09093 Mt) is assumed to be incinerated, 5% is openly burnt and remaining 15% is buried under ground. Hospitals of Pakistan produced 0.0976 Mt of waste for the inventory year at the rate of 2 kg/bed/day [22] for 133,707 beds [23], of which 10% (i.e., 0.001 Mt) is assumed to be treated in incinerators.

About 4.59 Mt (25%) of MSW and 0.06 Mt of other waste (including 0.0004 Mt (10%) industrial, 0.0098 Mt (10%) hospital and 0.045 Mt (5%) hazardous waste) for the inventory year is assumed to be openly burnt [20].

Methodological equation The methodological equations for estimation of CO_2, CH_4 and N_2O from waste incinerated and openly burnt differ due to the different factors that affect emissions level [12], 12. In case of CO_2 emissions, the amount of fossil carbon is the determining factor, while CH_4 and N_2O emissions mostly depend on type of technology and conditions of incineration process [12].

The CO_2 emissions from waste incineration and open burning are estimated using the following equation:

$$\text{Emissions}_{\text{CO2}} = \sum i(\text{IW}_i \times \text{CCW}_i \times \text{FCF}_i \times \text{EF}_i \times 12/44), \tag{2}$$

where $\text{Emission}_{\text{CO2}}$ is the total CO_2 emissions (GgCO_2/year), i is the MSW is the municipal solid waste, HW is the hazardous waste, CW is the clinical waste, SS is the sewage sludge, IW_i is the amount of incinerated/burnt waste of type i (Gg/year), CCW_i is the fraction of carbon content in waste of type i, FCF_i is the fraction of fossil carbon in waste of type i, EF_i is the burn out efficiency of combustion of incinerators for waste type i (Fraction), 12/44 is the conversion of C to CO_2.

The N_2O emissions from waste incinerated and openly burnt are calculated using the following equation:

$$\text{Emissions}_{\text{N2O}} = \sum i\left(\text{IW}_i \times \text{EF}_i\right) \times 10^{-6}, \tag{3}$$

where $\text{Emission}_{\text{N2O}}$ is the total N_2O emissions (GgN_2O/year), IW_i is the amount of incinerated/burned waste of type i (Gg/year), EF_i is the aggregate N_2O emission factor for waste type i (kg N_2O/Gg), 10^{-6} is the conversion from kg to Gg.

The calculation of CH_4 emissions from waste incinerated and openly burnt are based on the following equation:

$$\text{Emissions}_{\text{CH4}} = \sum i\left(\text{IW}_i \times \text{EF}_i\right) \times 10^{-6}, \tag{4}$$

where $\text{Emission}_{\text{CH4}}$ is the total CH_4 emissions (Gg CH_4/year), IW_i is the amount of incinerated/burned solid waste of type i (Gg/year), EF_i is the aggregate N_2O emission factor for waste type i (kg N_2O/Gg), 10^{-6} is the conversion from kg to Gg.

Waste water handling and discharge

Anaerobic handling of domestic and industrial wastewater produces CH_4 emissions. The methods for estimating domestic and industrial wastewater CH_4 emissions are generally similar for both handling systems but employs different types of activity data and emission factors. Therefore, both wastewater systems are considered and discussed separately [13].

Domestic wastewater Pakistan in contrary to developed countries where domestic wastewater is mostly treated aerobically, treats only a small share of its domestic wastewater in sewers system, leaving a major share to end up in pits or latrines. The municipal sewer system may also get some industrial wastewater discharged directly into them where it combines with domestic wastewater, which is also dealt with domestic wastewater system.

The IPCC method of estimating domestic wastewater CH_4 emissions is a function of the amount of waste generated and emission factor characterizing the extent to which the generated waste produces CH_4 [13].

The IPCC method used in these estimations is based on the following equation:

$$\text{Emissions}_{\text{CH4}} = (\text{Totalorganicwaste} \times \text{Emissionfactor}) - \text{Methanerecovery}, \tag{5}$$

where $\text{Emission}_{\text{CH4}}$ is the total CH_4 emissions ($GgCH_4$/year), Total organic waste is the amount of organic waste generated from wastewater, Emission factor is the default factor that characterizes the extent of CH_4 emission, Methane recovery is the CH_4 recovered and flared or used for energy purposes.

Industrial wastewater Industrial wastewater may be mostly treated on site at facility level, while remaining that mixes with domestic system is dealt there with that system. Therefore, this method deals with industrial wastewater CH_4 emissions produced during its on-site treatment.

The IPCC method for estimating industrial wastewater CH_4 emissions is generally similar to the one used for domestic wastewater system (as simplified in Eq. 5). But, the method for industrial wastewater system is more complex in terms of activity data needs and the development of emission factors, which requires to track many types of wastewater from many different industries [13].

Human sewage

The IPCC guidelines provide guidance on the estimation of N_2O emissions only from human sewage which is a function of per capita protein intake annually. The default method accounts for intake of nitrogen only, i.e., faeces and urine, excluding nitrogen inputs from all other sources including industrial, kitchen, bath and laundry discharges [13].

Only the human sewage based on annual per capita intake of protein, has been included in the present method for estimating N_2O emissions from this source category using the following equation:

$$\text{Emissions}_{\text{N2O}} = \left(P_{\text{Annual}} \times \text{Frac}_{\text{NPR}} \times N_{\text{Pop}}\right) \times \text{EF}\big), \tag{6}$$

where $\text{Emission}_{\text{N2O}}$ is the total N_2O emissions (GgN_2O/year), P_{Annual} is the annual protein per capita consumption (Protein in kg/person/year), Frac_{NPR} is the fraction of nitrogen in protein (kg N/kg protein), EF is the emission factor for N_2O (kg N_2O–N/kg Sewage-N produced).

Results and discussion

Emission profile of waste sector

The estimates of waste sector's emissions show that waste is responsible for 26.94 $MtCO_2e$ emissions accounting for 23.88 (88.6%) Mt of CH_4, 2.67 (9.9%) Mt of N_2O and 0.39 (1.45%) Mt of CO_2 emissions (Table 1). CH_4 is mostly the dominant GHG as compared to CO_2 and N_2O [24] which may be due to the conducive anaerobic conditions for CH_4 generation [10]. According to IPCC, waste landfills have been recognized as the large source of anthropogenic CH_4 emissions which account for 3–19% of the anthropogenic sources in the world [13]. In category analysis, SWD is found as major contributor emitting 14.30 Mt of CH_4 emissions which is 53.1% of total waste emissions followed by wastewater handling and discharge with emissions of 11.43 (42.4%) and waste incineration and opening burning with emissions of 1.21 (4.5%) $MtCO_2e$ (Fig. 1).

The CH_4 emissions from any type of waste mainly depend on three factors, i) the quantity of untreated waste disposed to SWDS; ii) fraction of DOC in the waste; and iii) CH_4 generation rate (k). Solid waste is mostly composed of materials having higher fraction of DOC and 'k' as compared to any other type of waste. Higher CH_4 emissions from SWDS may be associated with the higher quantities of solid waste disposed to SWDS having higher fraction of DOC and 'k'. The results are in line with findings reporting 18% (in 2010), 58% (2020) and 85% (2025) higher CH_4 emissions as compared to that of 2005, which was due to the increased quantity of MSW (under rapidly surging population) disposed to the landfills [25].

Solid waste disposal

The composition of MSW and ISW disposed to SWDS is shown in Fig. 2. The MSW of about 11.02 Mt disposed to SWDS is composed of 40.3% food waste, 19.5% other waste, 13.4% garden waste, 11.3% paper waste, 7.9% wood waste, 5% nappies waste and 2.5% textile waste. The ISW of about 0.0013 Mt disposed to SWDS is composed of 47.2% expired

Table 1 Emission profile of waste sector, by gas for 2019–2020 ($MtCO_2e$)

Source category	Emissions (CO_2e)			
	CO_2	CH_4	N_2O	Total
Waste	0.39	23.88	2.67	26.94
Solid waste disposal		14.30		14.30
Waste incineration and open burning	0.39	0.64	0.18	1.21
Wastewater handling and discharge		8.94	2.49	11.43

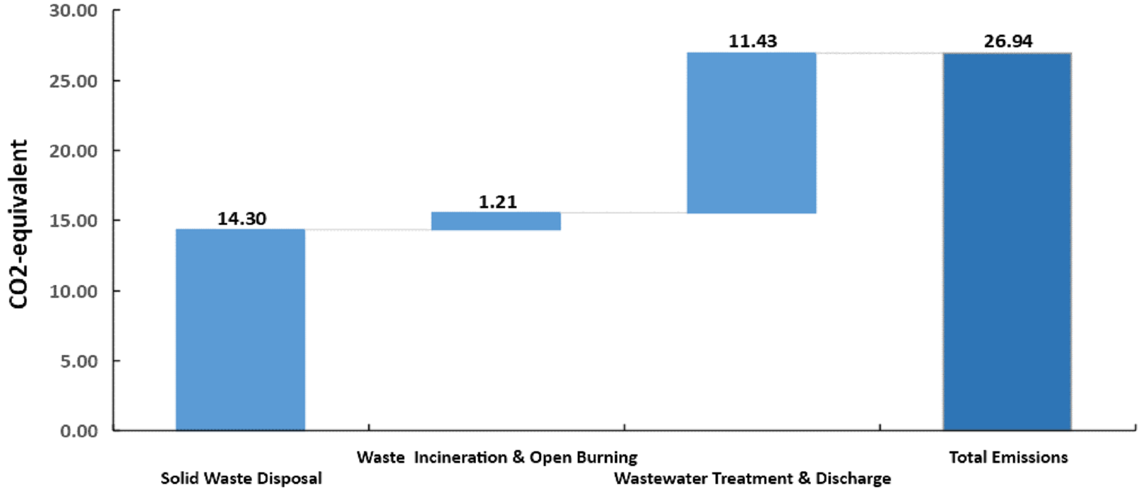


Fig. 1 Emission profile of waste sector, by category for 2019–2020 ($MtCO_2e$)

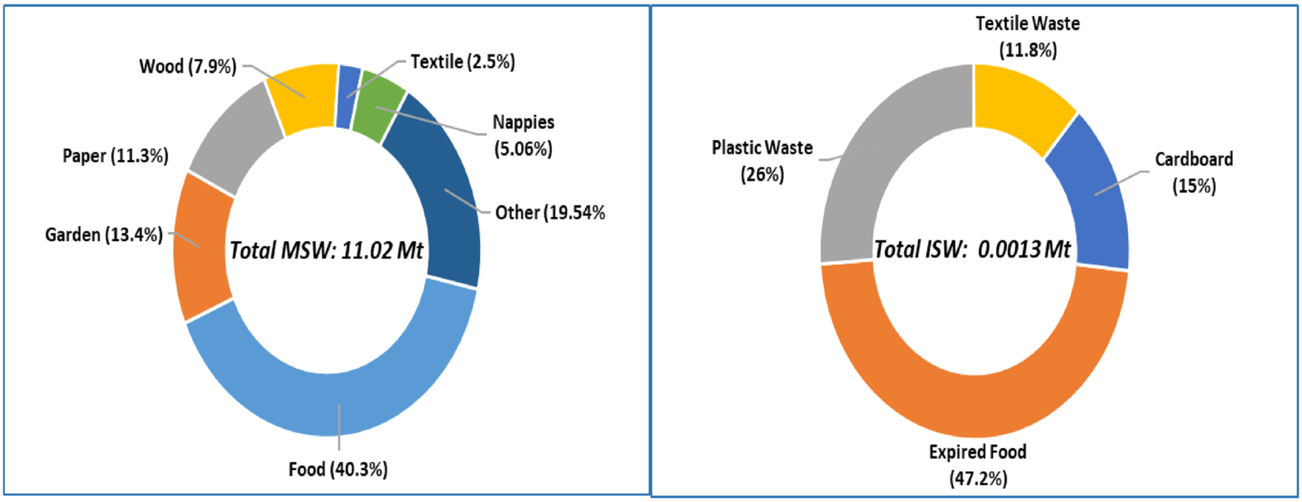


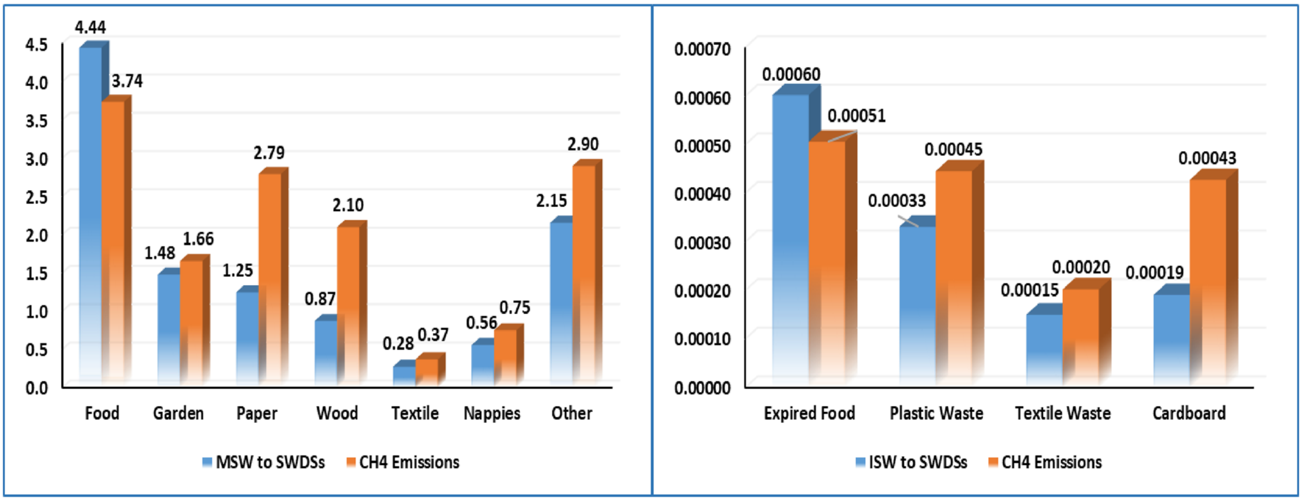
Fig. 2 Composition of MSW and ISW for 2019–2020 (Mt)

food, 26% plastic waste, 15% cardboard waste and 11.8% textile waste.

The decomposition of both MSW and ISW at SWDS results in CH_4 emissions of 14.304 $MtCO_2e$, of which 14.302 (99.98%) Mt is from MSW and 0.002 (0.01%) Mt is from ISW. The higher CH_4 emissions from MSW as compared to ISW may be attributed to the increased production and disposal of MSW to SWDS [25]. The quantity of components in MSW and ISW disposed to SWDS along with their corresponding CH_4 emission estimations are shown in Fig. 3.

The emission results of MSW, show that food waste is the major contributor with 3.74 Mt of CH_4 emissions constituting 26.12% of total MSW emissions. The other waste is the second major contributing category with 2.90 (20.3%) Mt emissions followed by paper waste with emissions of 2.79 (19.5%) Mt, wood waste with emissions of 2.10 (14.7%) Mt, garden waste with emissions of 1.66 (11.6) Mt, nappies waste with emissions of 0.75 (5.2%) and textile waste with 0.37 (2.6%) Mt of CH_4 emissions. In case of ISW, expired food waste emitting 0.0005 Mt of CH_4 emissions is major contributor which constitutes 32% of total emissions from ISW, followed by plastic waste emitting 0.00045 (28.2%) Mt emissions, cardboard waste emitting 0.00043 (27%) Mt emissions and textile waste emitting 0.0002 (12.8%) Mt of CH_4 emissions.

The reason for higher CH_4 emissions from food waste in MSW and ISW might be due to the higher quantity of food waste with associated higher CH_4 generation rate (0.085) as compared to any other type of waste. In case of MSW, higher CH_4 emissions from other and paper waste might also



(a) **(b)**

Fig. 3 **a** MSW versus CH_4 emissions. **b** ISW versus CH_4 emissions, for 2019–2020 ($MtCO_2e$)

be attributed to higher quantity of waste disposed to SWDS with associated higher CH_4 generation rate (0.045 for paper) as compared to wood waste (0.025 which is almost half than that of paper waste). While higher quantity of garden waste as compared to paper and wood waste produced lower CH_4, which might be due to lower fraction of DOC (0.200) available for degradation. Remaining small quantities of nappies and textile waste coupled with lower fraction of DOC were responsible for less CH_4 emissions as compared all other waste categories. In case of ISW, higher CH_4 emissions from plastic and cardboard as compared to textile waste might also be linked with higher quantities of plastic and cardboard waste disposed to SWDS.

It can be inferred from the results that both quantity of waste and CH_4 generation rates played significant role in CH_4 emissions from SWDS as mentioned in IPCC guidelines [12].

Waste incineration and open burning

The composition of waste incinerated and openly burnt along with corresponding emissions are shown in Fig. 4. Waste incinerated of about 0.75 Mt is composed of 86.55% MSW, 12.10% hazardous waste, 1.30% clinical waste and 0.05% industrial waste. While, openly burnt waste of about 4.65 Mt is composed of 98.80% MSW and 1.20% other waste. The corresponding emission data from both sources show that waste incineration and open burning is responsible for 1.21 $MtCO_2e$ emissions, of which 1.03 Mt emissions are from openly burnt waste which accounts for 85.4% of total

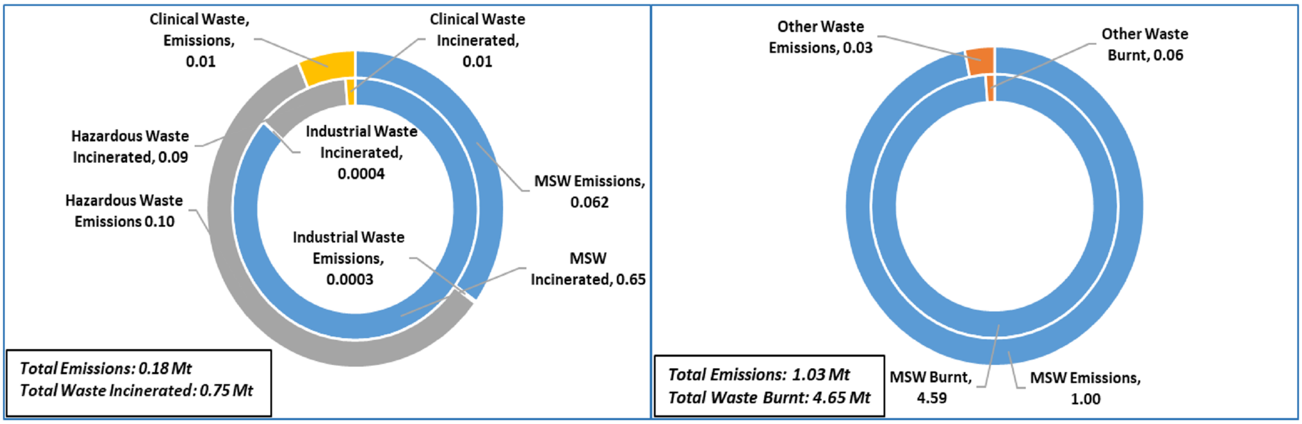


Fig. 4 **a** Waste incineration versus emissions. **b** Waste burnt versus emissions, for 2019–2020 ($MtCO_2e$)

emissions from this category followed by 0.18 (14.6%) Mt emissions from waste incineration.

The reason behind higher GHG emissions in case of open burning might be attributed to the higher amount of waste openly burnt, inefficient and uncontrolled combustion conditions (typically at low temperatures) as compared to waste incineration under highly efficient combustion conditions (at high temperatures) in modern refuse combustors with well-designed combustion chambers in a controlled environment, as endorsed by IPCC Refinement [26] and Environmental Protection Agency, USA [27] explaining the similar factors influencing emissions from open waste burning—combustion efficiency and type of waste and amount of waste being incinerated or openly burnt.

In case of waste incineration, hazardous waste is major emitting category with 0.10 $MtCO_2e$ emissions constituting 58.61% of emissions from waste incineration. MSW is the second major emitting category with 0.062 (34.90%) Mt emissions followed by clinical waste with 0.01 (6.29%) Mt emissions and industrial waste with 0.0003 (0.20%) Mt emissions. On the other hand, emissions from openly burnt waste are majorly from MSW with 1.00 (96.77%) Mt emissions followed by other waste with 0.03 (3.23%) $MtCO_2e$ emissions.

It was the large amount of hazardous and MSW waste that made them major categories responsible for emissions from waste incineration and open burning, respectively, endorsing waste type and amount as one of the factors influencing emissions as explained by Environmental Protection Agency, USA [27].

Wastewater handling and discharge

Wastewater handling and discharge is responsible for 11.43 $MtCO_2e$ emissions, of which 9.97 (87.24%) Mt is from domestic wastewater and 1.46 (12.76%) Mt is from industrial wastewater.

Domestic wastewater handling and discharge Domestic wastewater's emissions of 9.97 $MtCO_2e$ are constituent of 7.48 (75.1%) Mt of CH_4 emissions and 2.49 (24.9%) Mt of indirect N_2O emissions. The indirect N_2O emissions are based on the amount of nitrogen in human sewage along with industrial and commercial co-discharge.

i) CH_4 emissions

Domestic wastewater handling and discharge systems used by the population of various income groups along with associated MCFs [12] are shown in Table 2. Wastewater handling systems with associated CH_4 emissions by the population of various income groups are shown in Fig. 5 and Table 3. The emission results indicate that domestic wastewater handling and discharge systems are responsible for 9.97 $MtCO_2e$ emissions, of which 7.48 (75.07%) Mt are direct CH_4 emissions and 2.49 (24.93%) Mt are indirect N_2O emissions.

Table 2 Wastewater handling systems with associated methane correction factors

Handling system	ULIG (80% urban population)	UHIG (20% urban population)	Rural	MCF
Septic	14%	18%	0%	50%
Latrine	10%	10%	47%	10%
Other	3%	3%	0%	10%
Sewer	53%	53%	10%	13%
None	2%	16%	43%	0%

The vertical analysis of various wastewater handling systems under different income groups of urban and rural population shows that 7.48 $MtCO_2e$ of CH_4 emissions are constituent of 5.92 (79.08%) Mt emissions from urban low income group (ULIG) which is 80% of the urban population, 1.51 (20.14%) Mt emissions from urban high income group (UHIG) which is 20% of urban population and 0.06 (0.78%) Mt emissions from rural population.

In ULIG and UHIG, septic system is ranked first with septic CH_4 emissions of 2.73 $MtCO_2e$ and 0.79 $MtCO_2e$ constituting 46.1% and 52.4% of total emissions from both income groups, respectively. Similarly, sewer system is ranked second with sewer CH_4 emissions of 2.68 (45.4%) and 0.60 (40.1%) Mt from ULIG and UHIG respectively, followed by latrine system with latrine CH_4 emissions of 0.39 (6.6%) Mt and 0.09 (5.8%) Mt, respectively and other system with other CH_4 emissions of 0.12 (2%) Mt and 0.03 (1.7%) Mt, respectively. In case of rural population, latrine and sewer systems with CH_4 emissions of 0.05 (78.3%) Mt and 0.01 (21.7%) $MtCO_2e$ are ranked first and second major emitting systems, respectively. While, the septic, other and none handling systems are not found responsible for any of emissions.

In horizontal analysis, septic system is responsible for 3.52 (47.1%) $MtCO_2e$ septic CH_4 emissions in all income groups, of which 2.73 (77.6%) Mt and 0.79 (22.4%) Mt are from ULIG and UHIG, respectively; sewer system is responsible for 3.30 (44.1%) $MtCO_2e$ sewer CH_4 emissions, of which 2.68 (81.3%) Mt, 0.60 (18.3%) Mt and 0.01 (0.38%) Mt are from ULIG, UHIG and Rural, respectively; latrine system is responsible for 0.52 (6.9%) $MtCO_2e$ latrine CH_4 emissions, of which 0.39 (74.5%) Mt, 0.09 (16.8%) Mt and 0.05 (8.75%) Mt are from ULIG, UHIG and Rural, respectively; and other system is responsible for 0.14 (1.9%) $MtCO_2e$ other CH_4 emissions, of which 0.12 (81.6%) Mt and 0.03 (18.4%) Mt are from ULIG and UHIG, respectively.

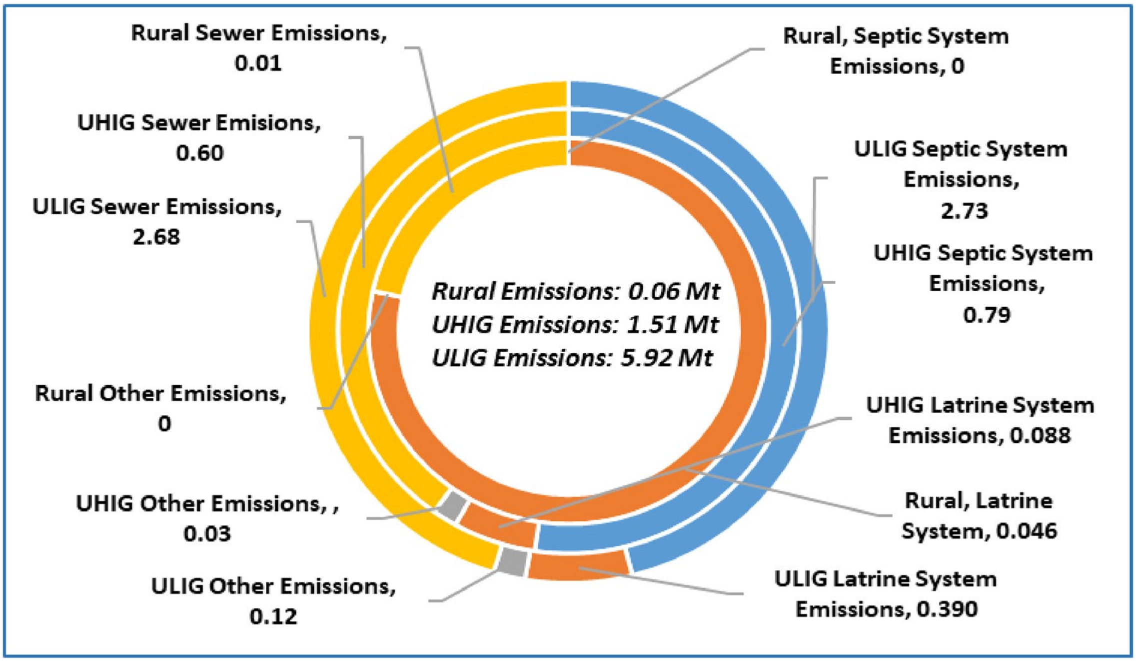


Fig. 5 Wastewater handling system and associated CH_4 emissions for 2019–2020 ($MtCO_2e$)

Table 3 Wastewater handling systems with associated methane emissions for 2019–2020 ($MtCO_2e$*)*

	ULIG	UHIG	Rural	Total
Septic	2.73	0.79	0	3.52
Latrine	0.39	0.09	0.05	0.52
Other	0.12	0.03	0	0.14
Sewer	2.68	0.60	0.01	3.30
None	0	0	0	0
Total	5.92	1.51	0.06	7.48

The 'none' handling system is responsible for no emissions in any of the income group.

The amount of emissions from wastewater may largely be determined by population, wastewater handling systems and the associated MCFs. The highest CH_4 emissions across all handling systems from ULIG (79.1%) as compared to the UHIG (20.14%) and rural population (0.78%) conformed that it was higher population (80%) of ULIG that made it major emission group as compared to UHIG with 20% urban population. While small amount of CH_4 emissions from rural population might be attributed to the lower degree of utilization of handling systems (57%). The results endorsed the findings that population is the main determinant of the emissions from wastewater [24].

In case of handling systems, the large amount of septic CH_4 emissions (47%) and sewer CH_4 emissions (44.1%) across all population groups as compared to other handling systems (8.8%) might have come primarily due to their higher MCFs and the higher degree of their utilization by different population groups, in line with the findings of a scientific study on mitigation pathways for waste sector [24].

ii) N_2O emissions

The population of 211.77 million has produced 1.02 Mt of nitrogen in its effluent by consuming 0.48 Mt protein in the estimation year which (fraction: 1.25) is responsible for the 2.49 Mt indirect N_2O emissions. Indirect N_2O emissions from wastewater after disposal of effluent into waterways, lakes or the sea depend on population size producing the wastewater and nitrogen content in the wastewater based on average annual per capita protein generation/consumption [12]. N_2O emissions of 2.49 Mt may, therefore, be attributed to the amount of protein consumed by large population in the inventory year resulting in production of higher nitrogen content in its effluent discharged in the domestic wastewater. Emission attribution of N_2O with nitrogen content is also in accordance with the finding reporting that highest anthropogenic nitrogen content in the wastewater had the significant potential for N_2O emissions [28].

Industrial wastewater handling and discharge Industrial wastewater is responsible for CH_4 emissions of 1.46 $MtCO_2e$. The wastewater profile of different industries along with total Chemical Oxygen Demand (COD which measures the total material available for chemical oxidation, both biodegradable and non-biodegradable) in the wastewater from each of the industries is shown in Fig. 6. Industrial wastewater of 676.18 Mt from all industries accounted for in the estimation year produced 2.78 Mt COD which has resulted in the CH_4 emissions of 1.46 $MtCO_2e$ (Fig. 7).

Industries of dairy products and paper and pulp are major emission contributors emitting 0.574 (39.4%) Mt and 0.464 (31.8%) $MtCO_2e$ of CH_4 emissions, respectively. Meat and poultry, alcohol refining and sugar industry are third, fourth and fifth major emission contributors emitting 0.132 (9%) Mt, 104 (7.1%) Mt and 0.081 (5.6%) $MtCO_2e$ of CH_4 emissions, respectively. Rest all industries produced CH_4 emissions of 0.103 $MtCO_2e$ constituting 7% of total industrial emissions. Wastewater's potential to generate CH_4 depends on the amount of degradable organic material (COD in case of industrial wastewater) in the wastewater [12]. Higher CH_4 emissions from the industries of dairy products, and paper and pulp may, therefore, be associated with the higher amount of COD (1.09 and 0.88 Mt COD, respectively, for the inventory year) in the wastewater generated by these industries as compared to others. The other factor that might have added to higher emissions could be the higher amount of wastewater generated by these industries—higher the amount of wastewater with higher COD, higher would be the CH_4 emissions. It has been found that wastewater from paper industry contains large amounts of lignin-based recalcitrant organic material that can contribute to COD, similar to natural organic matter and easily degradable [29] This

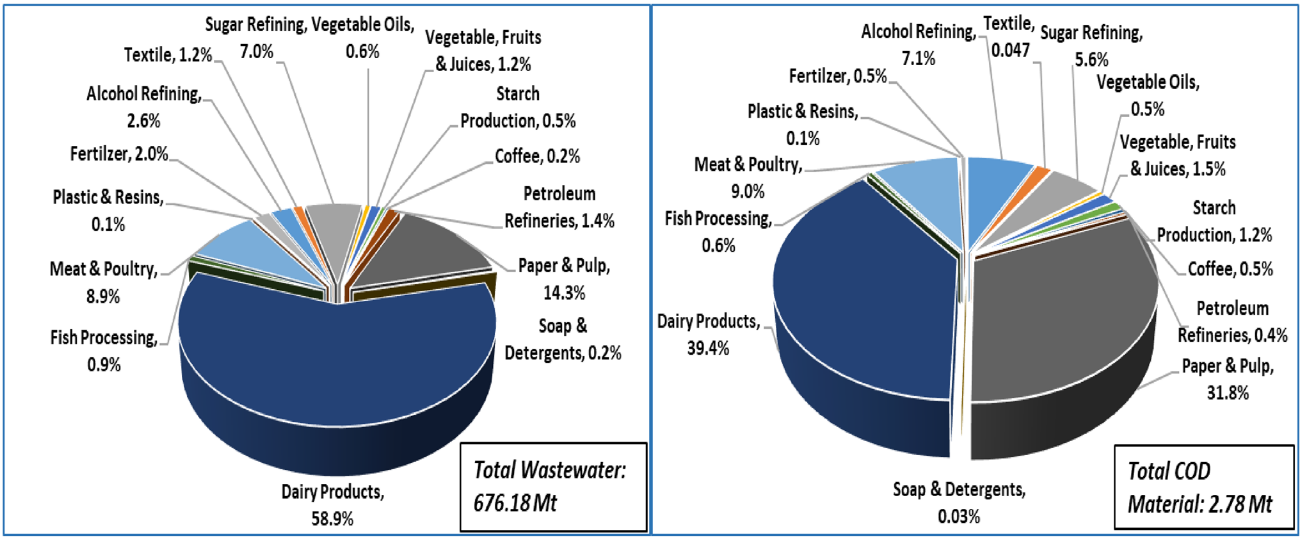
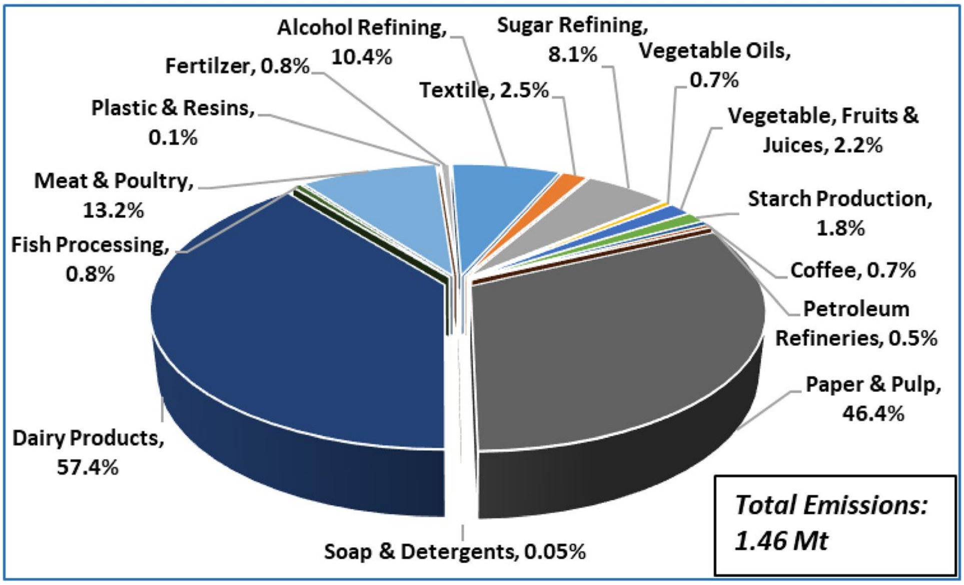


Fig. 6 Industrial wastewater profile with associated COD material for 2019–2020 (Mt)

Fig. 7 Industrial CH_4 emission profile for 2019–2020 ($MtCO_2e$)



supports the claim that it was the higher amount of COD in the dairy products, paper and pulp industry (as compared to others) which contributed to higher CH_4 emissions.

Pakistan in its first biennial update report highlighted waste as one of the critical sectors, which contributed 21.7 $MtCO_2e$ emissions in 2018. Social and economic pressures are predicting further increase in GHG emissions from the waste sector. Therefore, framing of waste management policies aligned with the country's ambitious commitments for reducing emissions is essential. The results of this study are intended for policy makers and mitigation analysts to expedite policy dialogues and action planning by providing an in-depth analysis of the country's waste management systems with associated GHG emissions, methods in quantifying emissions and targeted sectors for mitigation actions. Moreover, sector specific information or data on waste generation and GHG emissions in this study will provide an evidence based platform for advancing towards sustainable, low-emissions development strategies and solutions.

In Pakistan, municipal waste sector is primarily responsible for generating the large quantities of waste. Almost 60% of the total urban waste is disposed-off in dumpsites that are designated as dumping grounds by the municipal authorities. The higher emissions from SWD are, therefore, attributed to large quantities of solid waste generated by the municipal sector. Waste data with corresponding share of emissions from the municipal waste sector to overall GHG emissions must be taken seriously. Given the large quantities of waste generated and the current disposal scenario, there is a strong case for focusing on improved data management and mitigation technologies in deciding disposal options for solid waste by municipal sector.

Globally, increasing production of solid waste is being explored as an option for renewable energy source. The increasing volume of solid waste by the municipal sector together with high share in GHG emissions, requires Pakistan to develop a reform road map for its effective management. This necessitates Pakistan following the global pattern of using solid waste as an energy source, to evaluate the condition of waste resource energy recovery and possibility for further production of solid waste as a renewable energy source. Waste management has a strong influence on the environment as GHG emissions vary significantly between treatment options [30].

Thus, an overarching vision for the Pakistan waste sector is to prioritize solid waste prevention as highest priority followed by reuse, recycling, recovery and as a last resort, waste disposal [9]. Waste reusing and recycling and its increase use in energy recovery are the major changes in waste management that waste reforms and legislative measures have directed in last few years. Furthermore, municipal solid waste responsible for major share in waste emissions may be exploited as mitigation sector by recycling it into useful liquid and gas production through use of pyrolysis and gasification technology [31]. This technology has gained attention over waste incineration and open burning treatments because of its potential in reducing waste volume and producing valuable products, thereby contributing in GHG mitigations.

Conclusion

The estimation of GHG emissions from activities of solid and liquid waste handling, including SWD, waste incineration and open burning, wastewater handling and discharge starts with the compilation of activity data on waste generation, composition and its management. Waste generation data of both, solid and liquid is the basic activity data required for all such estimations. The recent available data for this study period shows that of Pakistan's total waste emissions (26.94 Mt), SWD with 14.30 (53%) $MtCO_2e$ emissions is the major emitting category in the country, followed by wastewater handling and discharge (11.43 Mt; 42.4%) and waste incineration and opening burning (1.21 Mt; 4.5%). The major chunk in the SWD's emissions, has come from organic fraction of food/expired food) of MSW and ISW, accounting for 11.02 (40.3%) Mt and 0.0013 (47.2%) $MtCO_2e$, respectively.

The rapid population growth and urbanization are signaling substantial increase in GHG emissions from waste sector in near future, which emphasizes on the need for mitigation actions to meet commitments of PA. The sector has potential to meet emission reduction commitments, because of its contribution to CH_4 emissions (23.88 Mt; 88.6% found in this study), a GHG with high global warming potential. For which, more accurate and detailed segregated information on data from responsible waste activities will be needed for accurate emission estimations. The findings of this study will thereby provide a scientific baseline in this regard.

Given the highest share of solid waste to the total GHG emissions from waste sector, the results of this study suggest to focus on solid waste more seriously. The current scenario of waste generation, collection and disposal strengthens the case for improved data management and mitigation technologies in deciding waste management options.

Data availability Most of the data generated or analyzed during this study are included in this article. Any further data information will be made available on reasonable request.

Declarations

Conflict of interest The corresponding author states that there is no competing or conflict of interest.

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