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GHG footprint of major cities in India

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ABSTRACT

Concentration of greenhouse gases (GHG) in the atmosphere has been increasing rapidly during the last century due to ever increasing anthropogenic activities resulting in significant increases in the temperature of the Earth causing global warming. Major sources of GHG are forests (due to human induced land cover changes leading to deforestation), power generation (burning of fossil fuels), transportation (burning fossil fuel), agriculture (livestock, farming, rice cultivation and burning of crop residues), water bodies (wetlands), industry and urban activities (building, construction, transport, solid and liquid waste). Aggregation of GHG (CO_2 and non-CO_2 gases), in terms of Carbon dioxide equivalent (CO_2e), indicate the GHG footprint. GHG footprint is thus a measure of the impact of human activities on the environment in terms of the amount of greenhouse gases produced. This study focuses on accounting of the amount of three important greenhouses gases namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and thereby developing GHG footprint of the major cities in India. National GHG inventories have been used for quantification of sector-wise greenhouse gas emissions. Country specific emission factors are used where all the emission factors are available. Default emission factors from IPCC guidelines are used when there are no country specific emission factors. Emission of each greenhouse gas is estimated by multiplying fuel consumption by the corresponding emission factor. The current study estimates GHG footprint or GHG emissions (in terms of CO_2 equivalent) for Indian major cities and explores the linkages with the population and GDP.

GHG footprint (Aggregation of Carbon dioxide equivalent emissions of GHG's) of Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad are found to be 38,633.2 Gg, 22,783.08 Gg, 14,812.10 Gg, 22,090.55 Gg, 19,796.5 Gg, 13,734.59 Gg and 91,24.45 Gg CO_2 eq., respectively. The major contributors sectors are transportation sector (contributing 32%, 17.4%, 13.3%, 19.5%, 43.5%, 56.86% and 25%), domestic sector (contributing 30.26%, 37.2%, 42.78%, 39%, 21.6%, 17.05% and 27.9%) and industrial sector (contributing 7.9%, 7.9%, 17.66%, 20.25%, 12.31%, 11.38% and 22.41%) of the total emissions in Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad, respectively. Chennai emits 4.79 t of CO_2 equivalent emissions per capita, the highest among all the cities followed by Kolkata which emits 3.29 t of CO_2 equivalent emissions per capita. Also Chennai emits the highest CO_2 equivalent emissions per GDP (2.55 t CO_2 eq./Lakh Rs.) followed by Greater Bangalore which emits 2.18 t CO_2 eq./Lakh Rs.

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1. Introduction

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds [1,2]. Concentration of greenhouse gases (GHG's) in the atmosphere has increased rapidly due to burgeoning anthropogenic activities coupled with population growth resulting in significant increase in the temperature of the earth. The energy radiated from the sun is absorbed by these gases making the lower part of the atmosphere warmer leading to phenomenon known as natural greenhouse gas effect. These effects were amplified with emission of gases from various anthropogenic activities consequent to industrialization and urbanization. Initially in 1950s based on infrared absorption model, CO_2 was identified as agents of changes in the atmosphere. Subsequently several studies confirmed that species of carbon (CO_2 and CH_4), Nitrogen (N_2O) and CFCs are crucial role in global warming and changes in the climate [3,4]. Increase in the concentration of these greenhouse gases results in global warming. Atmospheric concentrations of GHG gases have increased due to increasing emissions of GHGs during post industrialization era due to human activities. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) and sulfur hexafluoride (SF_6) are the major greenhouse gases. Among the GHG's, carbon dioxide is the most dominant gas causing global warming which accounts for nearly 77% of global total CO_2 equivalent GHG emissions [2].

In 1958, attempts were made towards the high-accuracy measurements of atmospheric CO_2 concentration and documented the changing composition of the atmosphere with the time series data [5,6]. The increasing abundances of two other major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O) in the atmosphere have been reported [7]. Methane levels were found to rise at a rate of about 1% per year [8–10] but then during 1990s its rate retarded to an average increase of 0.4% per year [11]. The increase in the concentration of other greenhouse gas N_2O is smaller, found to be about 0.25% per year [12,13]. Second class of greenhouse gases—the synthetic HFCs, PFCs, SF_6, CFCs, and halons did not exist in the atmosphere before the 20th century [14]. CF_4, a PFC, is detected in ice cores and appears to have an extremely small natural source [15].

The establishment of Inter-Governmental Panel on Climate Change (IPCC) in the year 1988 by United Nations organizations [16], and the formation of United Nations Framework Convention on Climate Change (UNFCCC) gave impetus towards quantifications of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with climate system. Adaptation of Kyoto Protocol in the year 1997 necessitated developed economies to reduce their collective emissions of six important greenhouse gases by at least 5.2% as compared to 1990 level during the period 2008–2012 [16]. These endeavors necessitated GHG accounting at the regional levels. Carbon dioxide, nitrous oxide and methane are the major greenhouse gases (GHG).

- *Carbon dioxide (CO_2) emissions*: CO_2 abundance was found to be significantly lower during the last ice age than over the last

10,000 years of the Holocene as per the initial measurements [17–19]. CO_2 abundances ranged between 280 ± 20 ppm from past 10,000 years present up to the year 1750 [20]. There was an exponential increase of CO_2 abundance during the industrial era to 367 ppm in 1999 [21–28] and to 379 ppm (in 2005).

- *Methane (CH_4) emissions:* Anthropogenic activities like fossil fuel production, enteric fermentation in livestock, manure management, cultivation of rice, biomass burning, and waste management releases methane to the atmosphere to a significant extent. Estimates indicate that human related activities release more than 50% of global methane emissions [31]. Natural sources of methane include wetlands, permafrost, oceans, freshwater bodies, non-wetland soils, and other sources such as wildfires. Accelerating rise in methane and nitrous oxide concentrations were reported during the 20th century and constant abundance of 700 ppb until the 19th century. A steady increase brought methane abundances to 1745 ppb in 1998 [28,29] and 1774 ppb in 2005 [30].
- *Nitrous oxide (N_2O) emissions*: Nitrous oxide (N_2O) is produced by both natural sources and human-related activities. Agricultural soil management, animal manure management, sewage treatment, mobile and stationary combustion of fossil fuel and nitric acid production are the major anthropogenic sources. Nitrous oxide is also produced naturally from a wide variety of biological sources in soil and water, particularly from microbial action [31] from the measurements for N_2O it is found that the relative increase during the industrial period is smaller (15%). The analysis showed a concentration of 314 ppb in 1998 [28], rising to 319 ppb in 2005.

Having understood the effects of various gases in the atmosphere it is also essential to understand that the climate regime is a complex, inter-related system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water and living things which is proving as a serious threat to global community and temperature [32–35]. Rising global temperatures will affect the local climatic conditions and also melt the fresh water ice glaciers causing the sea levels to rise Universal scientific understanding of this phenomena of earth's climate change is that it mainly caused by greenhouse gas emissions generated by human activity [4,36,37]. Extensive studies have been carried out to study the pattern of global and regional mean temperature with respect to time [38–40]. The atmospheric concentrations of carbon dioxide equivalent with the possibility of rise in global temperatures beyond certain levels were reported earlier [41]. The recent (globally averaged) warming by 0.5 °C is partly attributable to such anthropogenic emissions [41]. Change in climate also results in extreme weather events like very high temperatures, droughts and storms, thermal stress, flooding and infectious diseases. In the last 100 years the mean annual surface air temperature has increased by 0.4–0.6 °C in India [42,43]. This necessitates understanding the sources of global greenhouse gas emissions to implement appropriate mitigation measures.

1.1. GHG footprint and economic growth

The transition to a very low carbon economy needs elementary changes in technology, regulatory frameworks, infrastructure, business practices, consumption patterns and lifestyles [44,45]. Over the past decade, the emission of greenhouse gases into the atmosphere has caused a concern over global warming with efforts focusing on minimizing the emissions. Heavy industries are transferred to knowledge-based and service industries which are relatively cleaner as the economic development continues [46] and at advanced levels of growth, there was a gradual decrease of environmental degradation because of increased environmental awareness and enforcement of environmental regulation [41]. There is a need for a target to be set which aids the local and national governments to frame climate change policies and regulations. Carbon dioxide emissions and energy consumption are closely correlated with the size of a country's economy [45,47–49]. Carbon intensity is one of the most important indicators which help in measuring a country's CO_2 emission with respect to its economic growth. Carbon intensity refers to the ratio of carbon dioxide emissions per unit of economic activity, usually measured as GDP. It presents clear understanding of the impact of the factors that are responsible for emissions and also helps the policy makers in formulating future energy strategies and emission reduction policies [50]. The analysis of changes in carbon intensity in developing countries helps in optimizing fuel-mix and economic structure; meanwhile it also provides detailed information on the mitigation in the growth of energy consumption and related CO_2 emissions.

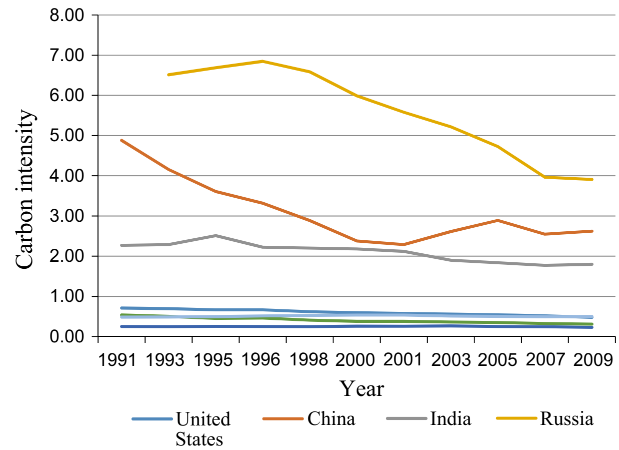

Fig. 1. Carbon intensity across the countries (kg CO_2/constant US $).

Carbon intensity value drops if there is a decrease in emissions or sharp rise in the economic growth of the country. Carbon dioxide emissions resulting from the consumption of energy from the major countries were compiled from published literatures (International Energy Statistics, United States Energy Information Administration, EIA). Economic growth represented in terms of constant US $ 2000 is obtained from the World Bank [51]. GDP in domestic currencies were converted using 2000 official exchange rates. Fig. 1 illustrates the carbon intensity trend across major carbon players in the globe. India's overall carbon intensity of energy use has marginally decreased in recent years despite coal's dominance. Strong penetrations of wind capacity and efficiency improvements in coal-based electricity production are some factors that are responsible for the decline of carbon intensity [52,53].

1.2. GHG footprint

Organizations and governments across the globe are looking for strategies to reduce emissions from greenhouse gases from anthropogenic origin, responsible for global warming [49,50]. The increasing interest in GHG footprint assessment comes as a result of growing public awareness of global warming. The global community now recognizes the need to reduce greenhouse gas emissions to mitigate climate change [54–57]. Many global metropolitan cities and organizations are estimating their greenhouse gas emissions and developing strategies to reduce their emissions.

"GHG footprint" is the total amount of greenhouse gases (GHG's) impacting the environment produced both directly and indirectly due to various human activities, expressed in equivalent tons of carbon dioxide. The total greenhouse gas emissions from various anthropogenic activities (sectors) from a particular region are expressed in terms of carbon dioxide equivalent, which indicate the GHG footprint of that region [58–60]. Carbon dioxide equivalent (CO_2e) is a unit for comparing the radiative forcing of a GHG (measure of influence of a climatic factor in changing the balance of energy radiation in the atmosphere) to that of carbon dioxide [61,62]. It is the amount of carbon dioxide by weight that is emitted into the atmosphere that would produce the same estimated radiative forcing as a given weight of another radiatively active gas [56].

Carbon dioxide equivalents are calculated by multiplying the weight of the gas being measured by its respective Global Warming Potential (GWP) [63–65]. It is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon dioxide. As defined by the Intergovernmental Panel on Climate Change (IPCC), a GWP is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change considering a fixed time period, such as 100 years (GWP_{100} expressed as a factor of carbon dioxide (whose GWP is standardized to 1). GWP depends on factors such as absorption of infrared radiation by a given species, spectral location of its absorbing wavelengths and the atmospheric lifetime of the species [66]. The Global warming potentials of major greenhouse gases over the next 20 years [67] are 1 for CO_2, 25 for CH4, 298 for nitrous oxide [1,2].

1.3. Need for estimation of GHG footprint

GHG footprints have the potential to reduce the impact on climate change by increasing consumer awareness and fostering discussions about the environmental impacts of products. It offers valuable information for the sustainable urban planning for policy makers and the local municipalities [68–74]. This entails quantification of sector-wise GHG's and computation of GHG footprint (aggregation of carbon equivalents of GHG's).

1.4. GHG emissions inventory in India

In India, research has been carried out on different features of climate change, but lacks dedicated reports on assessment of climate change. Asian Development Bank's report on "Climate change in Asia: India Country Report" was the first attempt to consolidate the information on climate change in India [75]. The study was limited to the collection of literature and certain studies on impacts of Climate Change on Agriculture, Water and Forests besides sea level rise [76]. Under Asia Least Cost Greenhouse Gas Abatement Strategy Project [77], a report was prepared on inventory of greenhouse gas emissions along with trace gases and sinks for the year 1990 and also the projections for 2020. In the year 2004, towards fulfillment of obligation under the UNFCCC, India submitted its Initial National Communication to the UNFCCC Secretariat which was a well synchronized report and serious efforts were made to assess the greenhouse gas emissions of anthropogenic origin and removal by sinks for at the 1994 level from fuel combustion and fugitive emissions from the energy sector, industrial processes and product use, agriculture sector, land use, land use change and forestry and waste management practices using revised Intergovernmental Panel on Climate Change Guidelines 1996 [78].

Currently, India is preparing its second national communication to the UNFCCC for the base year 2000. However, as there is a need for the latest data on greenhouse gas emissions from the country sector-wise.

1.4.1. GHG emissions in electricity generation sector in India

GHG emissions from electricity use occur during the generation of the electricity. Earlier studies have estimated the emission of gases due to power generation [54,55,79–86]. India's reliance on fossil-fuel based electricity generation has aggravated the problem of high carbon dioxide (CO_2) emissions from combustion of fossil fuels, primarily coal, in the country's energy sector. Combustion of coal at thermal power plants emits mainly carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x), other trace gases and air borne inorganic particulates, such as fly ash and suspended particulate matter [87]. Inventory of carbon dioxide emissions from coal based power generation in India are carried out from the present energy generation and the projections are done for next 2 decades [83]. A comprehensive emission inventory for megacity Delhi, India for the period 1990–2000 has been developed in which major CO_2 emissions were found from the power plants. Electricity generation, transport, domestic, industrial processes, agriculture emissions and waste treatment were the major sectors for which the emission inventories are done [81,86].

Measurements of CO_2 and other gases from coal based thermal power plants in India was done and the emission rates of the GHGs was found to be depended on factors like quality of coal mixture/oil, quantity used for per unit generation, age of the plant and amount of excess air fed into the furnace [79]. Study of large point source (LPS) emissions from India was carried out [89] for 1990 and 1995 using IPCC 1996 methodology, which showed CO_2 and SO_2 emissions being the major gases from the power plants.

Also, diverse studies have been carried out to calculate the greenhouse gas emissions resulting from the consumption of electricity for which a wide variety of fossil fuels are used for electricity generation [84,85,90–92].

1.4.2. GHG emissions in domestic and commercial sectors

Emissions from households and commercial establishments occur due to energy consumption for cooking, lighting, heating and household appliances. As per [93] there are various reasons why the study of household consumption patterns and energy requirements is of immense importance especially for a large developing country like India. Studies are carried out using input-output analysis and aggregated household expenditure survey data to calculate the CO_2 emissions from energy consumption for different groups of households for the year 1989–1990 [76,100,94–100,101]. In 2007, at the national level, the residential sector emitted 137.84 million tons of CO_2 equivalents and the commercial sector emitted 1.67 million tons of CO_2 equivalent. City level emission inventory for key sectors are carried out and household sector was responsible for a major portion of emissions, due to which it is a target sector for emission reduction targets which can be achieved in both existing and new housing which increases energy efficiency [102,103].

1.4.3. GHG emissions in transportation sector

Emissions from the road transport sector are directly related to the quantities of gasoline and diesel consumption and the increase in emissions has been due to an increase both in the number of motor vehicles on the road and the distance these vehicles travel [104]. Traffic composition of six mega cities of India (Delhi, Mumbai, Kolkata, Chennai, Bangalore and Hyderabad) shows that there is significant shift from the share of slow moving vehicles to fast moving vehicles and public transport to private transport [105,106]. Various studies have been carried out in India with regard to the emissions resulting from transportation sector [3,5,107,108,109]. Trends of energy consumption and consequent emissions of greenhouse gases such as CO_2, CH_4 and N_2O and ozone precursor gases like CO, NO_x and NMVOC in the road transport sector in India for the period from 1980 to 2000 have been studied and efforts being made to apportion the fuels, both diesel and gasoline, across different categories of vehicles operating on the Indian roads [104,105] and are the major sources of air pollutants in urban areas [81,88,110,111].

Estimation of emissions from vehicles has been studied using various model calculations [112]. There are studies that are carried out which calculate the emissions on the basis of the activity data, vehicle kilometer travelled, vehicle category and sub category [5,77,113,114,115,116]. Emission factors for Indian vehicles have been developed by the Automotive Research Association of India in co-ordination with MoEF, CPCB and State Pollution Control Boards [117]. Inventory estimates for the emissions of greenhouse gases and other pollutants and effects of vehicular emission on urban air quality and human health are studied in major urbanized cities in India [81,118–121].

1.4.4. GHG emissions in industrial sector

Industry is a major source of global greenhouse gas emissions. Industrial sector is responsible for approximately one-third of global carbon dioxide emissions through energy use [122]. In India, emission estimates from large point sources such as thermal power, steel industry, cement plants, chemical production and other industries are carried out by various researchers [123,124]. CO_2 emissions from iron and steel, cement, fertilizer and other industries like lime production, Ferro alloy production and aluminum production have been estimated [95,97].

Six industries in India have been identified as energy-intensive industries: Aluminum, cement, fertilizer, iron and steel, glass, and paper. The cement sector holds a considerable share within these energy-intensive industries [125,126]. At the country level, trends of greenhouse gas emissions from industrial processes are studied which shows 24,510 CO_2 equivalent emissions in the year 1990, 102,710 CO_2 equivalent emissions in 1994 and 168,378 CO_2 equivalent emissions in 2000 and 189,987.86 CO_2 equivalent emissions in 2007 [127–129]. Under the aegis of INCCA, a national-level GHG inventory for CO_2, CH_4 and N_2O inventory was published in 2010 for the base year 2007 which showed from industrial processes and product use [128].

1.4.5. GHG emissions in agriculture sector

Agricultural activities contribute directly to emissions of greenhouse gases through a variety of processes. The major agricultural sources of GHGs are methane (CH_4) emissions from irrigated rice production, nitrous oxide (N_2O) emissions from the use of nitrogenous fertilizers, and the release of carbon dioxide (CO_2) from energy sources used to pump groundwater for irrigation [130]. Where there is open burning associated with agricultural practices, a number of greenhouse gases are emitted from combustion. All burning of biomass produces substantial CO_2 emissions. In India the crop waste generated in the fields is used as feed for cattle, domestic biofuel and remainder is burnt in the field [131]. Rice paddy soils contain organic substrates, nutrients and water, thereby resulting to be an increasing source of methane resulting from anaerobic decomposition of carbonaceous substances [132]. The anaerobic bacterial processes in the irrigated rice cultivated fields are considered to be among the largest sources of methane emission [133] and the annual global contribution of methane is estimated to be approx. 190 Tgy^{-1} [134,135].

During recent years, several studies on CH_4 emission from Indian rice fields have been carried out by different researchers to study the effect of soil type, season, water regime, organic and inorganic amendments and cultivars [136–144]. Average methane flux varied significantly with different cultivars ranging between 0.65 and 1.12 $mg\,m^{-2}\,h^{-1}$ [120]. CH_4 emissions from Indian rice paddies, therefore, is estimated to be $3.6 \pm 1.4\,Tgy^{-1}$, which is lower than 4.2 (1.3 to 5.1) Tgy^{-1} obtained using the IPCC 1996 default emission factors [145]. India emitted 3.3 million tons of CH_4 in 2007 from 43.62 million ha cultivated [146–148]. Application of fertilizer-N in upland irrigated rice has led to increased N_2O emissions [96,97,146,147]. Total seasonal N_2O emission from different treatments ranged from 0.037 to 0.186 $kg\,ha^{-1}$ [68,83, 149–151].

1.4.6. GHG emissions in livestock sector

There are two major sources of methane emission from livestock: Enteric fermentation resulting from digestive process of ruminants and from animal waste management [30,31,152]. Animal husbandry accounts for 18% of GHG emissions that cause global warming [153]. Methane emission from enteric fermentation from Indian livestock ranged from 7.26 to 10.4 $MT\,year^{-1}$ [154]. In India more than 90% of the total methane emission from enteric fermentation is being contributed by the large ruminants (cattle and buffalo) and rest from small ruminants and others [155]. Production and emission of CH_4 and N_2O from manure depends on digestibility and composition of feed, species of animals and their physiology, manure management practices and meteorological conditions like sunlight, temperature, precipitation, wind, etc. [156,157].

In India, various studies have been carried out in which the emission inventories for enteric fermentation and manure management are done at the national level [81,89,91,145,153]. Total emission of methane from Indian livestock was estimated as 10.08 MT considering different categories of ruminants and type of feed resources available in different zone of the country [158]. CH_4 and N_2O country specific emission factors for bovines were found to be lower than IPCC-1996 default values. Inventory estimates were found to about 698 ± 27 Gg CH_4 from all manure management systems and 2.3 ± 0.46 t of N_2O from solid storage of manure for the year 2000 [145]. Using the emission factors provided in the report [146], it is estimated that the Indian livestock emitted 9.65 million tons in 2007. Buffalo is the single largest emitter of CH_4, as it constitutes 60% of the total CH_4 emission from this category, simply because of its large number compared to any other livestock species and also because of the large CH_4 emission factor with respect to others [76]. By using the IPCC guidelines, the total CH_4 emitted from enteric fermentation in livestock is found to be 10.09 million tons and emissions from manure management is estimated about 0.115 million tons of CH_4 and 0.07 thousand tons of N_2O are emitted [76].

1.4.7. GHG emissions inventory in waste sector

The main greenhouse gases emitted from waste management is CH_4. It is produced and released into the atmosphere as a by-product of the anaerobic decomposition of solid waste, where-by methanogenic bacteria break down organic matter in the waste. Similarly, wastewater becomes a source of CH_4 when treated or disposed anaerobically. It can also be a source of N_2O emissions as well due to protein content in domestically generated waste water [76,159,160]. Industrial wastewater with significant carbon loading that is treated under intended or unintended anaerobic conditions will produce CH_4 [30].

Waste landfills are considered to be largest source of anthropogenic emissions and the methane emissions from the landfill is estimated to account for 3–19% of the anthropogenic sources in the world [24]. Landfill gas, a mix of primarily CO_2 and CH_4, is emitted as a result of the restricted availability of oxygen during the decomposition of organic fraction of waste in landfills [161]. Attempts have been done to account methane emissions for select landfill sites in India [81,162–165,166].

CH_4 emission estimates were found to be about 0.12 Gg in Chennai from municipal solid waste management for the year 2000 which is lower than the value computed using IPCC [30]. Attempts are made to estimate the realistic values of methane emission from municipal solid waste landfills in India using default IPCC 1996 guidelines and triangular method (FOD method) shows that the triangular method is more realistic and can be used in estimation in global basis [167]. The existing situation of municipal solid waste management in major cities in India are assessed and parameters like waste quantity generated, waste generation rate, physical composition and characterization of MSW in each of the cities are carried out [168]. Solid waste generated in Indian cities increased from 6 Tg in 1947 to 48 Tg in 1997 [169] with per capita increase of 1–1.33% per year [170]. As per INCCA (2010) [83], 604.51 Gg of CH_4 was emitted from solid waste disposal sites in India.

Methane is generated from two categories of waste water—domestic and industrial. The main factor in determining the extent of CH_4 production is the amount of degradable organic fraction in the wastewater [171] that is commonly expressed in terms of biochemical or chemical oxygen demand (BOD) or (COD). Methane emissions from disposal and treatment of industrial and municipal solid waste (MSW) are not a prominent source in India, except in large urban centers. In India, methane emissions from domestic/commercial and industrial waste water are found to be 861 Gg and 1050 Gg respectively for the year 2007 and about 15.81 Gg of nitrous oxide is emitted from domestic/commercial waste water sector [95,96,128].

2. Objectives

Objectives of the current communication is to assess the GHG footprint of major cities in India through quantification of sector-wise GHG emissions and computation of Carbon dioxide equivalent (CO_2 eq.).

3. Method

Method involved (i) sector-wise quantification of GHG emissions, (ii) computation of carbon dioxide equivalent (CO_2e) of the non-CO_2 gases using their respective global warming potential (GWP) and (iii) aggregation of these CO_2e represents GHG footprint of a respective region

3.1. Study area

GHG footprint has been assessed for eight major metropolitan cities (> 4 million populations as per 2011 census) in India: Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad. Among these except Ahmedabad, all cities fall under the Class X (earlier class A1) cities as per the classification of Ministry of Finance [172]. Table 1 lists spatial location, population and GDP (Gross Domestic Product) for all chosen cities. Spatial locations of the cities are depicted in Fig. 2.

Table 1
Spatial location, population and GDP of major metropolitan cities in India.

Cities	Latitude and longitude[a]	Population (2009)[b]	GDP (constant prices 'crores) for 2009[c]
Delhi	28°25′N and 76°50′E	16,127,687	219,360.35
Greater Mumbai	18.9°N and 72.8°E	12,376,805	274,280.15
Kolkata	22°34′N and 88°24′E	4503,787	136,549.41
Chennai	13°04′N and 80°17′E	4611,564	86,706.92
Greater Bangalore	12°59′N and 77°37′E	8881,631	90,736.07
Hyderabad	17°28′N and 78°27′E	6007,259	76,254.10
Ahmedabad	23.02°N and 72.35°E	5080,596	64,457.80

[a] [102,149,173–178].
[b] [179,180].
[c] [181].

(i). *Delhi*: Delhi is the capital of India with long history, covering an area of 1483 km² with a population of 16,127,687 (in 2009). This city borders Uttar Pradesh state to the east and Haryana on the north, west and south. In 2009, Delhi had a GDP of Rs. 219,360 crores at constant prices which primarily relies on the integral sectors like power, telecommunications, health services, construction and real estate [182].

(ii). *Greater Mumbai (Bombay)*: Greater Mumbai, the capital of Maharashtra is one of the major port cities, located at the Coast of Arabic Sea in the west coast in India. Greater Mumbai region consists of Mumbai city district and Mumbai sub urban district. It covers a total area of 603.4 km² with a population of 12,376,805 (in 2009), which is also the commercial and entertainment capital of India generating GDP of Rs. 274,280 crores at constant prices contributing to 5% of India's GDP [183,184].

(iii). *Kolkata (Calcutta)*: Kolkata, the capital of West Bengal with core area of the city is flat and is located on the east bank of Hooghly River. The Municipal Corporation of Kolkata covers an area of 187 km² with a population of 4503,787 (in 2009). GDP of Kolkata in the year 2009 was estimated to be Rs. 136, 549 crores at constant prices resulting in being a major commercial and financial hub in the parts of Eastern and North-Eastern India.

(iv). *Chennai (Madras)*: Chennai, the capital of the state of Tamil Nadu is located on the Coromandel Coast of the Bay of Bengal having a population of 4611,564 in the year 2009, with an area of 174 km² which is expanded to 426 km² by the city corporation in the year 2011. The economy of the city majorly depends on sectors like automobile, software services, health care industries and hardware manufacturing resulting in estimated GDP of Rs. 86,706 crores at constant prices during the year 2009 [185].

(v). *Greater Bangalore*: Greater Bangalore is the principal administrative, cultural, commercial and knowledge capital of the state Karnataka which covers an area of 741 km² and a estimated population of 8881,631 during the year 2009. During the year 2009, Bangalore's economy of Rs. 90,736 crores at constant prices makes it one of the major economic centres in India. Economy depends on information technology, manufacturing industries, biotechnology and aerospace and aviation industries [186].

(vi). *Hyderabad*: Hyderabad, the capital of Andhra Pradesh is located at the north part of the Deccan plateau with a population of 6007,259. Municipal Corporation of Hyderabad covers an area of 179 km² whereas Greater Hyderabad is spread over an area of 650 km². Economic sector depends on traditional manufacturing, knowledge sector and tourism resulting in a GDP of Rs. 76,254 crores at constant prices in the year 2009.

(vii). *Ahmedabad*: Ahmedabad an industrial city is situated on the banks of Sabarmati River in north-central Gujarat. It covers an area of 205 km² with a population of 5080,596 in the year 2009. Ahmedabad is the second largest industrial centre in western India after Mumbai. Automobile sector, textiles, pharmaceutical and real estate are the major sectors

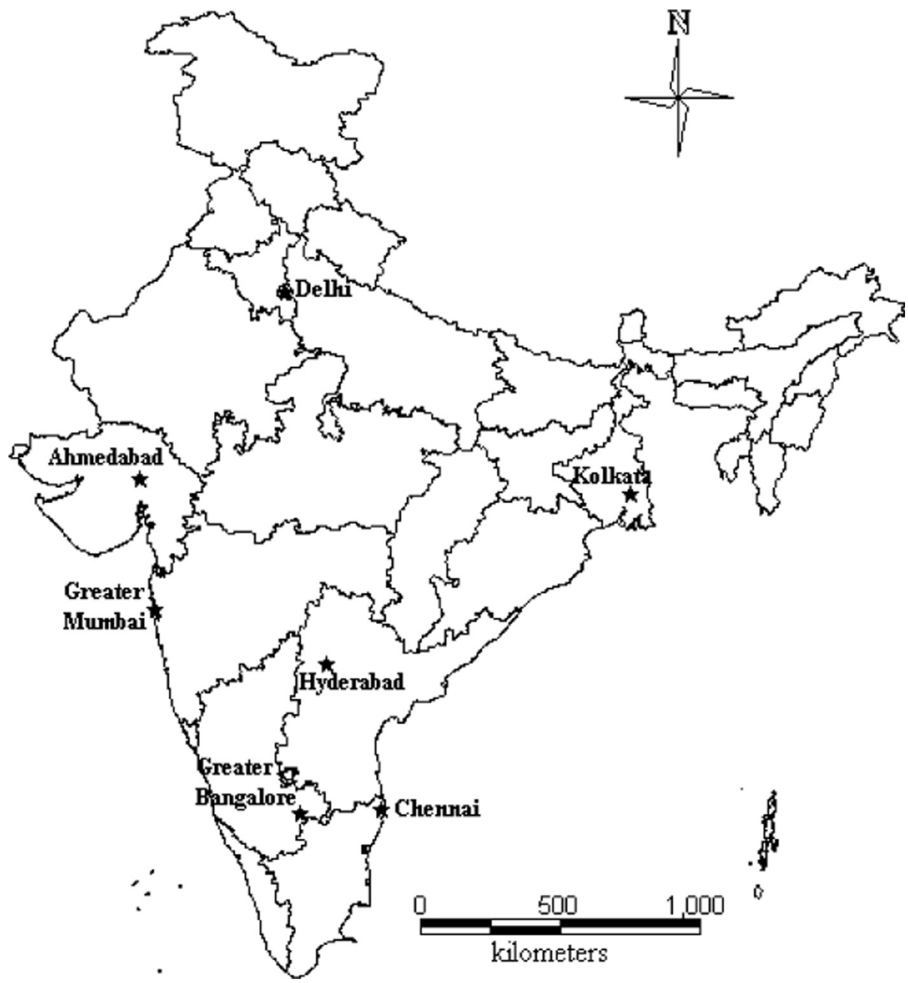

Fig. 2. Study area—major cities in India.

contributing to economy which stands at Rs. 64,457 crores at constant prices in the year 2009.

3.2. Quantification of greenhouse gases (GHG's)

The major three greenhouse gases quantified are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The non-CO_2 gases are converted to units of carbon dioxide equivalent (CO_2e) using their respective global warming potential (GWP), which represents the GHG footprint for the respective region. The total units of CO_2e then represent a sum total of the global warming potential of all 3 major greenhouse gases, which represents GHG footprint. The major categories considered for GHG emission inventory are (i) energy: electricity consumption, fugitive emissions, (ii) domestic or household sector, (iii) transportation, (iv) industrial sector, (v) agriculture related activities, (vi) livestock management and (vii) waste sector.

National greenhouse gas inventories compiled from various sources have been used for calculation of GHG emissions. Country specific emission factors were compiled from the published literatures. In the absence of country specific emission factors default emission factors of IPCC have been used. Emission of each GHG is estimated by multiplying fuel consumption by the corresponding emission factor. Total emissions of a gas from all its source categories [187–189], emissions are summed as given in Eq. (1).

$$Emissions_{Gas} = \sum_{Category} A \times \text{EF} \tag{1}$$

where $Emissions_{Gas}$ is the emissions of given gas from all its source categories; A is the amount of individual source category utilized which generates emissions of the gas under consideration; EF is the emission factor of a given gas type by type of source category.

3.2.1. GHG emissions from electricity consumption

Combustion of fossil fuels in thermal power plants during electricity generation results in the emission of greenhouse gases into the atmosphere. Carbon dioxide (CO_2), oxides of sulfur (SO_x), nitrogen oxides (NO_x), other trace gases and air borne inorganic particulates, such as fly ash and suspended particulate matter (SPM) are the most important constituents emitted from the burning of fossil fuels from thermal power [188,190]. The emissions computed based on the consumption in the following categories: domestic, commercial, industrial and others which include consumption in railways, street lights, municipal water supply, sewage treatment etc. based on the amount of electricity consumed by these sectors. The total greenhouse gas emissions have been calculated on the basis of fuel consumption required for the generation of electricity using Eq. (2),

$$\begin{aligned}\text{Emissions(t)} = {} & \text{Fuel consumption(kt)} \\ & \times \text{Net calorific value of fuel}\left(\text{TJ kt}^{-1}\right) \\ & \times \text{Emission factor}\left(\text{t TJ}^{-1}\right)\end{aligned} \tag{2}$$

Electricity is generated from various sources (coal, hydro, nuclear, gas, etc.). The proportion of electricity generated from

Table 2
Net calorific value (NCV), CO_2, CH_4 and N_2O emission factors of different fuel.

Fuel	NCV ($TJ\ kt^{-1}$)	CO_2 EF ($t\ TJ^{-1}$)[a,b]	CH_4 EF ($t\ TJ^{-1}$)[b]	N_2O EF ($t\ TJ^{-1}$)[b]
Coal	19.63	95.81	0.001	0.0015
Natural gas	48	56.1	0.001	0.0001
Naphtha	44.5	73.3	0.003	0.0006
Diesel oil	43.33	74.1	0.003	0.0006
Natural gas	48.632	64.2	0.003	0.0006
LSHS	40.19	73.3	0.003	0.0006
RFO	40.4	77.4	0.003	0.0006
LSFO	41	73.3	0.003	0.0006
HFO	40.2	73.3	0.003	0.0006

Note: NCV—Net Calorific Value, EF—Emission factor, LSHS—Low Sulfur Heavy Stock, RFO—Residual Fuel Oil, LSFO—Low Sulfur Fuel Oil, HFO—Heavy Fuel Oil.
[a] [30,83].
[b] [83].

Table 3
Net Calorific Value (NCV), CO_2, CH_4 and N_2O emission factors of domestic fuels used in the study.

Fuel	NCV ($TJ\ kt^{-1}$)	CO_2 EF ($t\ TJ^{-1}$)[a,b]	CH_4 EF ($t\ TJ^{-1}$)[b]	N_2O EF ($t\ TJ^{-1}$)[b]
LPG	47.3	63.1	0.005	0.0001
PNG	48	56.1	0.005	0.0001
Kerosene	43.8	71.9	0.01	0.0006

Note: LPG—Liquified Petroleum Gas, PNG—Piped Natural Gas.
[a] [30].
[b] [83].

each source for each study region is compiled from the secondary source (State electricity board, Central electrical Authority, etc.). Quantity of respective fuel is computed with the knowledge of the relative share of fuel and the quantity of fuel required for generating one unit of electricity (such as 0.7 kg Coal required for generation of 1 unit (kW h) of electricity). The data related to electricity consumption in different cities is taken from the respective electricity boards providing electricity to that city. Table 2 lists the emission factors and the net calorific values of respective fuels.

The total emissions obtained from the amount of fuel consumed is then distributed into major sectors like domestic, commercial, industrial and others based on the amount of electricity consumed in that sector during the inventory year 2009–2010. Apart from the fuel consumption on the basis of electricity consumption which is calculated, the fuel consumption and the emissions resulting thereby is also determined for the auxiliary consumption in the power plants located within the city boundary and the transmission loss resulting from these power plants.

3.2.2. Fugitive emissions

Fugitive emissions are the intentional or unintentional release of GHGs which occurs during the extraction, production, processing or transportation of fossil fuels. Exploration for oil and gas, crude oil production, processing, venting, flaring, leakages, evaporation and accidental releases from oil and gas industry are the sources of CH_4 emission [83,172]. Refinery throughput is the total amount of raw materials processed by a refinery or other plant in a given period. In the present study the emissions from refinery crude throughput is calculated from the refineries present within the city boundary as per Eq. (3).

$$\text{Emissions(Gg)} = \text{Refinery crude throughput (Million tons)} \times \text{Emission factor (Gg/Million tons)} \tag{3}$$

The methane emission factor for refinery throughput is 6.75904×10^{-5} Gg/million tons (IPCC, 2000, 2006).

3.2.3. GHG emissions from domestic sector

Large demand for energy consumption in the domestic sector is predominantly due to activities like cooking, lighting, heating and household appliances. As per the Census of India [179], in urban areas, most commonly used fuel is Liquified Petroleum Gas (47.96%), followed by firewood (22.74%) and kerosene (19.16%). Electricity consumption in the households is another major source of energy utilization in the urban households. The pollution caused by domestic fuel use is a major source of emissions in cities which causes indoor air pollution contributing to overall pollution. Utilization of type of fuels in households also affects the air pollution.

The emissions resulting from electricity consumption in domestic sector is attributed to this sector. Greenhouse gas emissions from fuel consumption in domestic sector can be calculated [189] by using Eq. (4). Table 3 lists NCV and emission factors for the domestic fuels.

$$\text{Emissions(t)} = \text{Fuelconsumption(kt)} \times \text{Net calorific value of fuel} \left(\text{TJ kt}^{-1}\right) \times \text{Emission factor} \left(\text{t TJ}^{-1}\right) \tag{4}$$

3.2.4. GHG emissions from transportation sector

Transportation sector is one of the dominant anthropogenic sources of greenhouse gases (GHGs) in to the atmosphere. The urban population predominantly depends on road transport due to which there is an increase in sales of vehicles in urban areas every year. Type of transport and fuel, apart from type of combustion engine, emission mitigation techniques, maintenance procedures and age of the vehicle are the major factors on which road transportation emissions depend upon [189]. Emissions is estimated from either the fuel consumed (fuel sold data) or the distance travelled by vehicles approach. Bottom-up approach was implemented based on number of registered vehicles, annual vehicle kilometers travelled and corresponding emission factors for the estimation of gases from road transportation sector [81,110]. At national level studies, fuel consumption approach is used to calculate the emissions from road transport [76].

Bottom-up approach is used in this study in which emissions are calculated using the data available on number of vehicles, distance travelled in a year and the respective emission factor for different vehicles. Emissions from road transport are calculated as per Eq. (5) and emission factors are listed in Table 4 [117,81,91].

$$E_i = \sum (\text{Veh}_j \times D_j) \times E_{i,j,\text{km}} \tag{5}$$

where E_i is the emission of the compound (i); Veh_j is the number of vehicles per type (j); D_j is the distance travelled in a year per different vehicle type (j); $E_{i,j,\text{km}}$ is the Emission of compound (i), vehicle type (j) per driven kilometer.In this study the number of registered vehicles in the inventory year 2009 is taken from the 'Motor Transport Statistics' of respective states and also from 'Road Transport Year Book (2007–2009) [192] when the city level data is not available from the local transport authority. Supreme Court passed an order in July 1998 for converting all public transport vehicles to CNG mode in Delhi, which marked a beginning of CNG vehicles in India [193,194]. Emissions from the number of vehicles using Compressed Natural Gas (CNG) as a fuel are also calculated in the major cities where CNG is introduced to mitigate the emissions resulting from transportation. Vehicle kilometer

Table 4
CO_2, CH_4 and N_2O emission factors for different type of vehicles.

Type of vehicle	CO_2 EF ($g\ km^{-1}$)[a]	CH_4 EF ($g\ km^{-1}$)[b]	N_2O EF ($g\ km^{-1}$)[b]
Motor cycles, scooters & mopeds	27.79	0.18	0.002
Cars and jeeps	164.22	0.17	0.005
Taxis	164.22	0.01	0.01
Buses	567.03	0.09	0.03
Light motor vehicles (passengers)	64.16	0.18	0.002
Light motor vehicles (goods)	273.46	0.09	0.03
Trucks and lorries	799.95	0.09	0.03
Tractors and trailers	515.2	0.09	0.03

[a] Emission factor development for Indian Vehicles, The Automotive Research Association of India, 2007 [117].
[b] [81,191].

Table 5
Vehicle kilometers travelled (VKT). *Source*: Ramachandra and Shwetmala, 2009 [119].

Type of vehicles	VKT
Motor cycles, scooters & mopeds	10,000
Cars and Jeeps	15,000
Taxis	30,000
Buses	60,000
Light motor vehicles (passengers)	40,000
Light motor vehicles (goods)	40,000
Trucks and lorries	30,000
Tractors and trailers	5000

travelled per year values are taken from the Central Pollution Control Board of India [115,194]. The annual average mileage values of different vehicles used are given in Table 5 [110]

GHG emissions for major cities in India were calculated considering the fuel consumption for navigation in major ports of Mumbai, Kolkata and Chennai. 2006 IPCC guidelines provide methodology to calculate emissions from navigation [30]. Using the ship type in the ports and gross registered tonnage (GRT), the total fuel consumed is calculated, using which the emissions are calculated. The type of ships and GRT data is available from [195]. Eq. (6) is used to compute the emissions using the fuel consumption in different ship types using GRT and ship type data as given below,

$$\text{Emissions(t)} = \text{Fuel consumption(kt)} \times \text{Net calorific value of fuel}\left(\text{TJ kt}^{-1}\right) \times \text{Emission factor}\left(\text{t TJ}^{-1}\right) \quad (6)$$

Container = 8.0552 + (0.00235 × GRT).
Break Bulk (General Cargo) = 9.8197 + (0.00413 × GRT).
Dry Bulk = 20.186 + (0.00049 × GRT).
Liquid Bulk = 14.685 + (0.00079 × GRT).

High Speed Diesel (HSD), Light Diesel Oil (LDO) and Fuel Oil are the major fuels used for shipping in India [93]. The average of NCV values and emission factors are used to calculate the emissions for fuel consumption. CO_2 emission factors for Fuel Oil and HSD/LDO are taken as $77.4\ t\ TJ^{-1}$ and $74.1\ t\ TJ^{-1}$, respectively. CH_4 and N_2O emission factors are taken as $0.007\ t\ TJ^{-1}$ and $0.002\ t\ TJ^{-1}$,

Table 6
Values used to calculate GHG emissions from fertilizer industry.
Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories [30].

Parameter	FR ($GJ\ t^{-1}$ NH_3 produced)	CCF ($kg\ C\ GJ^{-1}$)	COF (fraction)
Value	37.5	15.30	1

respectively, for navigation [29]. At the country level, the emissions
from shipping are calculated using the fuel consumption data [78,96,110].

3.2.5. GHG emissions from industry sector

Greenhouse gas emissions are produced from a wide variety of industrial activities. Industrial processes that chemically or physically alter materials are the major emission sources. The blast furnace in the iron and steel industry, manufacturing of ammonia and other chemical products from fossil fuels used as chemical feedstock and the cement industry are the major industrial processes which releases considerable amount of CO_2 [30]. There is no data available for calculation of emissions from small and medium scale industries which are present in thousands of number in the major cities. In this study the emissions are calculated from the major polluting industrial processes from the industries which are located within the city boundaries. In cities like Mumbai, presence of large petrochemical plants, fertilizer plants and power plants leads to emissions [196].

The greenhouse gases estimated for the type of industries located within the city boundaries based on the availability of the data are discussed below. Ammonia (NH_3) is a major industrial chemical and the most important nitrogenous material produced. Ammonia gas is directly used as a fertilizer, paper pulping and also in manufacturing of chemicals [29]. Ammonia production data is obtained from the fertilizer industry and emission factors and other parameters (Table 6) are obtained from IPCC 2006 guidelines. Emission from ammonia production is calculated as per Eq. (7).

$$E_{CO_2} = AP \times FR \times CCF \times COF \times 44/12 - R_{CO_2} \quad (7)$$

where E_{CO_2} is the emissions of CO_2 (kg); AP is the ammonia production (t); FR is the fuel requirement per unit of output ($GJ\ t^{-1}$ ammonia produced); CCF is the carbon content factor of the fuel (kg C/GJ); COF is the carbon oxidation factor of the fuel (fraction); R_{CO_2} is the CO_2 recovered for downstream use (urea production) in kg.

Glass industry can be divided into 4 major groups: Containers, flat (window) glass, fibre glass and specialty glass. Limestone ($CaCO_3$), dolomite Ca, $Mg(CO_3)_2$ and soda ash (Na_2CO_3) are the major glass raw materials which are responsible for the emission of CO_2 during the melting process. Eq. (8) is used when there is no data available on glass manufactured by process or the carbonate used in the manufacturing of glass.

$$CO_2\text{emissions} = Mg \times EF \times (1 - CR) \quad (8)$$

where CO_2 emissions is the emissions of CO_2 from glass production (t); Mg is the mass of glass produced (t); EF is the default emission factor for manufacturing of glass (tCO_2/t glass); CR is the cullet ratio for process (fraction).

Table 7 gives the values of different parameters that are used to calculate GHG emissions from glass industry. In the present study fuel consumption data available from major industries present within the major city boundary limits are used to calculate the emissions where all data is available. The fuel consumption by the industries for the year 2009–10 is obtained from their annual

Table 7
Values used to calculate GHG emissions from glass industry.
Source: 2006 IPCC Guidelines for National Greenhouse Gas Inventories [30].

Parameter	Emission factor (t CO_2/t glass)	Cullet ratio
Value	0.2	0.5

reports using which the emissions are calculated accounting for fuel utilization.

3.2.6. GHG emissions from agriculture related activities

Agriculture related activities such as paddy cultivation, agricultural soils and burning of crop residue are considered for quantification of GHG. Flooded rice fields are one source of methane emissions. During the paddy growing season, methane is produced from anaerobic decomposition of organic material in flooded rice fields which escapes to the atmosphere through the rice plants by the mechanism of diffusive transport [197,198]. Oxygen supply is seized to the soil from the atmosphere due to the flooding of rice fields which leads to anaerobic fermentation of organic matter in the soil, resulting in the production of methane [199].

There are three processes of methane release into the atmosphere from paddy fields. The major phenomenon being the CH_4 transport through rice plants [200,201]. This accounts for more than 90% of the total CH_4 emissions. Methane loss as bubbles (ebullition) from paddy soils is also a common and significant mechanism. The least important process is the diffusion loss of CH_4 across the water surface [197]. The emission of methane from rice fields depends on various factors such as amendment of organic and inorganic fertilizers, characteristics of rice varieties, water management and soil environment [123]. CH_4 emissions from rice cultivation have been estimated by multiplying the seasonal emission factors by the annual harvested areas. The total annual emissions are equal to the sum of emissions from each sub-unit of harvested area which is calculated using Eq. (9) [26].

$$CH_4\ Rice = \sum_{i,j,k}\left(\mathrm{EF}_{i,j,k} \times A_{i,j,k} \times 10^{-6}\right) \tag{9}$$

where $CH_{4\,Rice}$ is the annual methane emissions from rice cultivation (Gg CH_4 yr^{-1}); $EF_{i,j,k}$ is the seasonal integrated emission factor for *i*, *j*, and *k* conditions (kg CH_4 ha^{-1}); $A_{i,j,k}$ is the annual harvested area of rice for *i*, *j*, and *k* conditions (ha yr^{-1}); *i*, *j* and *k* are the represent different ecosystems, water regimes, type and amount of organic amendments and other conditions under which CH_4 emissions from rice may vary.

It is advisable to calculate the total emissions as a sum of the emissions over a number of conditions, when carrying out studies at city levels the following methodology from Revised IPCC 1996 guidelines is used [197].

$$F_c = EF \times A \times 10^{-9} \tag{10}$$

where F_c is the estimated annual emission of methane from a particular rice water regime and for a given organic amendment (Gg yr^{-1}); EF is the methane emission factor integrated over integrated cropping season (g m^{-2}); *A* is the annual harvested area cultivated under conditions defined above. It is given by the cultivated area times the number of cropping seasons per year (m^2 yr^{-1}).

The above methodology is used because the area of paddy fields based on the type of ecosystem (irrigated, rain fed, deep water and upland) is not available at city level. Seasonally integrated emission factor of 10 g m^{-2} is used which is obtained from the revised 1996 IPCC guidelines [198].

Agricultural soils contribute towards the emission of 2 major GHGs: methane and nitrous oxide. N_2O is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate and denitrification is the process of anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. This methodology, therefore, estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers, deposited manure, crop residues, sewage sludge), or of mineralization of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils [30,202].

The emissions of N_2O resulting from anthropogenic N inputs or N mineralization occur through both a direct pathway (i.e., directly from the soils to which the N is added/released), and through two indirect pathways: (i) following volatilization of NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent redeposition of these gases and their products NH_4^+ and NO_3^- to soils and waters; and (ii) after leaching and runoff of N, mainly as NO_3^-, from managed soils. Total N_2O emissions are given by,

$$N_2O\mathrm{emissions} = N_2O_{Direct}\mathrm{emissions} + N_2O_{Indirect}\mathrm{emissions} \tag{11}$$

3.2.6.1. Direct N_2O emissions.

The sources included for estimation of direct N_2O emissions are, synthetic N fertilizers, organic N applied as fertilizer, urine and dung N deposited on pasture, range and paddock by grazing animals, N in crop residues, N mineralization associated with loss of soil organic matter resulting from change of land use or management of mineral soils and drainage/management of organic soils.

$$N_2O_{Direct} - N = N_2O - N_{NInput} + N_2O - N_{OS} + N_2O - N_{PRP} \tag{12}$$

where N_2O_{Direct}–N is the annual direct N_2O–N emissions from managed soils (kg N_2O–N yr^{-1}); N_2O–$N_{N\ Input}$ is the annual direct N_2O–N emissions from N inputs to managed soils (kg N_2O–N yr^{-1}); N_2O–N_{OS} is the annual direct N_2O–N emissions from managed organic soils (kg N_2O–N yr^{-1}); N_2O–N_{PRP} is the annual direct N_2O–N emissions from urine and dung inputs to grazed soils (kg N_2O–N yr^{-1}).

$$N_2O - N_{NInput} = [[(F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \times EF_1] + [F_{SN} + F_{ON} + F_{CR} + F_{SOM})_{FR} \times EF_{1FR}]] \tag{13}$$

where F_{SN} is the annual amount of synthetic fertilizer N applied to soils (kg N yr^{-1}); F_{ON} is the annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils (kg N yr^{-1}); F_{CR} is the annual amount of N in crop residues (above-ground and below-ground), including N-fixing crops and from forage/pasture renewal, returned to soils (kg N yr^{-1}); F_{SOM} is the annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, (kg N yr^{-1}); EF_1 is the emission factor for N_2O emissions from N inputs (kg N_2O–N (kg N_{input})$^{-1}$); EF_{1FR} is the emission factor for N_2O emissions from N inputs to flooded rice (kg N_2O–N (kg N_{input})$^{-1}$).

$$N_2O - N_{OS} = [(F_{OS,CG,Temp} \times EF_{2CG,Temp}) + (F_{OS,CG,Trop} \times EF_{2CG,\ Trop}) + (F_{OS,F,Temp,NR} \times EF_{2F,Temp,NR}) + (F_{OS,F,Temp,NP} \times EF_{2F,Temp,NP}) + (F_{OS,F,Trop} \times EF_{2F,Trop})] \tag{14}$$

where EF_2 is the emission factor for N_2O emissions from drained/managed organic soils, kg N_2O–N ha^{-1} yr^{-1}.

The subscripts CG, F, Temp, Trop, NR and NP refer to Cropland and Grassland, Forest Land, Temperate, Tropical, Nutrient Rich, and Nutrient Poor, respectively.

$$N_2O-N_{PRP} = \left[\left(F_{PRP,CPP} \times EF_{3PRP,CPP}\right) + \left(F_{PRP,SO} \times EF_{3PRP,SO}\right)\right] \quad (15)$$

where F_{PRP} is the annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock, kg N yr^{-1}; EF_{3PRP} is the emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals, kg N_2O–N (kg N_{input})$^{-1}$.

The subscripts CPP and SO refer to Cattle, Poultry and Pigs, and Sheep and other animals respectively.

$$F_{ON} = F_{AM} + F_{SEW} + F_{COMP} + F_{OOA} \quad (16)$$

$$F_{AM} = N_{MMSAvb} \times [1-(Frac_{FEED} + Frac_{FUEL} + Frac_{CNST})] \quad (17)$$

$$F_{PRP} = \sum_T [(N_{(T)} \times N_{ex(T)} \times MS_{(T,PRP)}] \quad (18)$$

where F_{ON} is the total annual organic N fertilizer applied to soils other than by grazing animals (kg N yr^{-1}); F_{AM} is the annual amount of animal manure N applied to soils (kg N yr^{-1}); F_{SEW} is the annual amount of total sewage N that is applied to soils (kg N yr^{-1}); F_{COMP} is the annual amount of total compost N applied to soils (kg N yr^{-1}). $N_{MMS\ Avb}$ is the amount of managed manure N available for soil application, feed, fuel or construction (kg N yr^{-1}); $Frac_{FEED}$ is the fraction of managed manure used for feed; $Frac_{FUEL}$ is the fraction of managed manure used for fuel; $Frac_{CNST}$ is the fraction of managed manure used for construction; $N_{(T)}$ is the number of head of livestock species/category T in the country; $N_{ex(T)}$ is the annual average N excretion per head of species/category T (kg N $animal^{-1}$ yr^{-1}); $MS_{(T,PRP)}$ is the fraction of total annual N excretion for each livestock species/category T that is deposited on pasture, range and paddock.

Organic soils contain more than 12 to 18% of organic carbon. Indian soils are generally deficient of organic carbon (less than 1%). Only some soils in Kerala and Northeast hill regions contain higher organic carbon (5%). So the area under organic soil has been taken as nil [135].

3.2.6.2. Indirect N_2O emissions. Sources considered for estimation of indirect N_2O emissions include synthetic N fertilizers, organic N applied as fertilizer, urine and dung N deposited on pasture, range and paddock by grazing animals, N in crop residues, N mineralization associated with loss of soil organic matter resulting from change of land use or management of mineral soil. The N_2O emissions from atmospheric deposition of N volatilized from managed soils is estimated by Eq. 19.

$$N_2O_{(ATD)} - N = [(F_{SN} \times Frac_{GASF}) + ((F_{ON} + F_{PRP}) \times Frac_{GASM})] \times EF_4 \quad (19)$$

where $N_2O_{(ATD)}$–N is the annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O–N yr^{-1}); F_{SN} is the annual amount of synthetic fertilizer N applied to soils (kg N yr^{-1}); $Frac_{GASF}$ is the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x (kg N volatilized (kg of N applied)$^{-1}$); F_{ON} is the annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils (kg N yr^{-1}); F_{PRP} is the annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock (kg N yr^{-1}); $Frac_{GASM}$ is the fraction of applied organic N fertilizer materials (F_{ON}) and of urine and dung N deposited by grazing animals (F_{PRP}) that volatilizes as NH_3 and NO_x (kg N volatilized (kg of N applied or deposited)$^{-1}$); EF_4 is the emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N–N_2O (kg NH_3–N + NO_x–N volatilized)$^{-1}$).

N_2O emissions from leaching and run off in regions where leaching and runoff occurs are estimated using Eq. (20).

$$N_2O_{(L)} - N = (F_{SN} + F_{ON} + F_{PRP} + F_{CR} + F_{SOM}) \times Frac_{LEACH-(H)} \times EF_5 \quad (20)$$

where $N_2O_{(L)}$–N is the annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs (kg N_2O–N yr^{-1}); F_{SN} is the annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs (kg N yr^{-1}); F_{ON} is the annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs (kg N yr^{-1}); F_{PRP} is the annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs (kg N yr^{-1}); F_{CR} is the amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs (kg N yr^{-1}); F_{SOM} is the annual amount of N mineralized in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs (kg N yr^{-1}); $Frac_{LEACH\text{-}(H)}$ is the fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff (kg N (kg of N additions)$^{-1}$); EF_5 is the emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N (kg N leached and runoff)$^{-1}$).

Conversion of $N_2O_{(ATD)}$–N and $N_2O_{(L)}$–N emissions to N_2O emissions is done using Eq. (21).

$$N_2O_{(ATD)/(L)} = N_2O_{(ATD)/(L)} - N \times 44/28 \quad (21)$$

Large quantities of agricultural wastes are produced from the farming systems in the form of crop residue. Burning of crop residues is not a net source of CO_2 because the carbon released to the atmosphere during burning is reabsorbed during the next growing season [197]. However it is a significant net source of CH_4, CO, NO_x and N_2O. In this study the emissions are calculated for two GHGs namely CH_4 and N_2O. Non-CO_2 emissions from crop residue burning were calculated using Eq. (22).

$$EBCR = \sum crops(A \times B \times C \times D \times E \times F) \quad (22)$$

where EBCR is the emissions from residue burning; *A* is the crop production; *B* is the residue to crop ratio; *C* is the dry matter fraction; *D* is the fraction burnt; *E* is the fraction actually oxidized; *F* is the emission factor.

3.2.7. GHG emissions from livestock sector

Major activities resulting in the emission of greenhouse gases from animal husbandry are (i) enteric fermentation and (ii) manure management. Enteric fermentation is a digestive process by which carbohydrates are broken down by the activity of micro-organisms into simple molecules for absorption into the blood stream. Factors like type of digestive tract, age and weight of the animal, quality and quantity of feed consumed affects the amount of CH_4 released. Ruminant livestock (cattle, sheep) are the major sources of CH_4 whereas moderate amounts are released from non-ruminant livestock (pigs, horses). CH_4 emissions from enteric fermentation is calculated using Eq. 23,

$$Emissions = EF_{(T)} \times N_{(T)} \times 10^{-6} \quad (23)$$

where Emissions is the methane emissions from enteric fermentation (Gg CH_4 yr^{-1}); $EF_{(T)}$ is the emission factor for the defined livestock population (kg CH_4 $head^{-1}$ yr^{-1}); $N_{(T)}$ is the number of head of livestock species/category T; T is the species/category of livestock.

Table 8
Methane emission factors used to calculate emissions from livestock management.

Livestock	EF for enteric fermentation ($kg\ CH_4\ head^{-1}\ year^{-1}$)[a]	EF for manure management ($kg\ CH_4\ head^{-1}\ year^{-1}$)[a]
Dairy cattle	46	3.6
Non dairy cattle	25	2.7
Young cattle	25	1.8
Buffaloes	55	4
Sheep	5	0.3
Goats	5	0.2
Pigs	1	4
Horses and ponies	18	1.6

[a] [30].

To estimate the total emissions from enteric fermentation, the emissions from different categories and sub-categories are summed together.

Methane emissions from manure management is calculated using Eq. (24),

$$\text{Emissions} = EF_{(T)} \times N_{(T)} \times 10^{-6} \tag{24}$$

where Emissions is the methane emissions from manure management ($Gg\ CH_4\ yr^{-1}$); $EF_{(T)}$ is the emission factor for the defined livestock population ($kg\ CH_4\ head^{-1}\ yr^{-1}$); $N_{(T)}$ is the number of head of livestock species/category T; T is the species/category of livestock.Nitrous oxide emissions from manure management is calculated through Eq. (25),

$$\text{Emissions} = EF_{(T)} \times N_{(T)} \times N-\text{excretion} \times 10^{-6} \tag{25}$$

where Emissions is the nitrous oxide emissions from manure management ($Gg\ CH_4\ yr^{-1}$); $EF_{(T)}$ is the emission factor for the defined livestock population ($kg\ N\ head^{-1}\ yr^{-1}$); $N_{(T)}$ is the number of head of livestock species / category T; T is the species/category of livestock; N-excretion is the nitrogen excretion value for the livestock ($kg\ head^{-1}\ yr^{-1}$).

CH_4 and N_2O emission factors used in this study are shown in Table 8. N_2O emissions from manure management, for livestock species of dairy cattle, non-dairy cattle, young cattle and buffaloes, nitrogen excretion rates are taken as 60, 40, 25 and 46.5 kg $head^{-1}\ yr^{-1}$, respectively.

3.2.8. GHG emissions from waste sector

Methane (CH_4) is the major greenhouse gas emitted from the waste sector. Three major categories are considered in this study: Municipal solid waste disposal, domestic waste water and industrial waste water. Considerable amounts of methane (CH_4) are produced from the treatment and disposal of municipal solid waste. CH_4 produced at solid waste disposal sites (SWDS) contributes approximately 3–4% to the annual global anthropogenic greenhouse gas emissions [27]. The IPCC methodology for estimating CH_4 emissions from SWDS is based on the First Order Decay (FOD) method which assumes that CH_4 and CO_2 are formed when the degradable organic component in waste decays slowly throughout a few decades. No methodology is provided for N_2O emissions from SWDS because they are not significant. Emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition, and then the bacteria responsible for decay consumes the degradable carbon in the waste due to which the emission decreases [30]. CH_4 emissions from solid waste disposal system is calculated by Eq. (26),

$$\text{Emissions } CH_4 = [MSW \times MCF \times DOC \times DOC_f \times F \times 16/12] - R] \times (1 - OF) \tag{26}$$

where MSW is the mass of waste deposited ($Gg\ yr^{-1}$); MCF is the methane correction factor for aerobic decomposition in the year of deposition (fraction); DOC is the degradable organic carbon in the year of deposition (Gg C/Gg waste); DOC_f is the fraction of degradable organic carbon which decomposes (fraction); F is the fraction of CH_4 in generated landfill gas (fraction); R is the methane recovery ($Gg\ yr^{-1}$); 16/12 is the molecular weight ratio CH_4/C (ratio); OF is the oxidation factor (fraction).

Methane (CH_4) correction factor (MCF) accounts for the fact that unmanaged SWDS produce less CH_4 from a given amount of waste than anaerobic managed SWDS. MCF of 0.4 is used in this study for unmanaged and shallow landfills [30]. Degradable Organic Carbon value of 0.11 is obtained from [203], fraction of degradable organic carbon that decomposes (DOC_f) is taken as 0.5 [27], fraction of CH_4 (F) in generated landfill gas is taken as 0.5 [30] and it is considered that the there is no CH_4 recovery in the disposal sites in the major cities and oxidation factor is taken as zero for unmanaged and uncategorized solid waste disposal system.

When treated or disposed anaerobically, wastewater can be a source of methane (CH_4) and also nitrous oxide (N_2O) emissions. Domestic, commercial and industrial sectors are the sources of wastewater. The waste water generated may be treated on site or in a centralized plant or disposed untreated nearby to water bodies. Wastewater in closed underground sewers is not believed to be a significant source of CH_4. The waste water in open sewers will be subjected to heating from the sun and the sewer conditions may be stagnant causing anaerobic conditions to emit CH_4 [203]. There is a variation in the degree of wastewater treatment in most developing countries. Domestic wastewater is treated in centralized plants, septic systems or may be disposed of in unmanaged lagoons or waterways, via open or closed sewers. Though the major industrial facilities may have comprehensive onsite treatment, in few of the cases industrial wastewater is discharged directly into the water bodies [30].

The extent of CH_4 production depends primarily on the quantity of degradable organic material in the wastewater, the temperature and the type of treatment system. More CH_4 is yielded from wastewater with higher COD or BOD concentrations when compared to wastewater with lower COD or BOD concentrations. Rise in temperature will also increase the rate of CH_4 production. N_2O is associated with the degradation of nitrogen components (urea, nitrate and protein) in the wastewater. Domestic wastewater mainly includes human sewage mixed with other household wastewater, from sources such as effluent from shower drains, sink drains, washing machines, etc. [30]. The equation used to estimate CH_4 emissions from domestic wastewater is given by Eq. (27),

$$CH_4 \text{ emissions} = [\textstyle\sum_{i,j}(U_i \times T_{i,j} \times EF_j)](TOW - S) - R \tag{27}$$

where CH_4 Emissions is the CH_4 emissions in inventory year ($kg\ CH_4\ yr^{-1}$); TOW is the total organics in wastewater in inventory year ($kg\ BOD\ yr^{-1}$); S is the organic component removed as sludge in inventory year (kg BOD yr^{-1}); U_i is the fraction of population in income group i in inventory year; $T_{i,j}$ is the degree of utilization of treatment/discharge pathway or system, j, for each income group fraction i in inventory year; i is the income group: rural, urban high income and urban low income; j is the each treatment/discharge pathway or system; EF_j is the emission factor (kg CH_4 kg BOD); R is the amount of CH_4 recovered in inventory year (kg CH_4 yr^{-1}).Emission factor (EF_j) is calculated using the below Eq. (28),

$$EF_j = Bo \times MCF_j \tag{28}$$

where EF_j is emission factor (kg CH_4 kg BOD), j is each treatment/discharge pathway or system, Bo is maximum CH_4 producing capacity (kg CH_4 kg BOD), MCF_j is methane correction factor (fraction).The total amount of organically degradable material in the wastewater (TOW) is a function of human population and BOD generation per person. It is expressed in terms of biochemical oxygen demand (kg BOD $year^{-1}$) and is given by Eq. (29),

$$TOW = P \times BOD \times 0.001 \times I \times 365 \tag{29}$$

where TOW is total organics in wastewater in inventory year (kg BOD yr^{-1}), P is country population in inventory year (person), BOD is country-specific per capita BOD in inventory year (g person day^{-1}), 0.001 is conversion from grams BOD to kg BOD, I is correction factor for additional industrial BOD discharged into sewers (for collected the default is 1.25 and for uncollected default is 1.00).

Nitrous oxide (N_2O) emissions can occur as both direct and indirect emissions. Direct emissions are from the treatment plants and indirect emissions from wastewater after disposal of effluent into waterways, lakes or the sea. Direct emissions of N_2O may be generated during both nitrification and denitrification of the nitrogen present [30]. The equation for estimating N_2O emissions from wastewater effluent is given by Eq. (30),

$$N_2O\ emissions = N_{effluent} \times EF_{effluent} \times 44/28 \tag{30}$$

where N_2O emissions is N_2O emissions in inventory year (kg N_2O yr^{-1}), $N_{effluent}$ is nitrogen in the effluent discharged to aquatic environments (kg N yr^{-1}), $EF_{effluent}$ is emission factor for N_2O emissions from discharged to wastewater (kg N_2O–N kg N). 44/28 is conversion of kg N_2O–N into kg N_2O.

$EF_{effluent}$ of 0.005 kg N_2O–N/kg N is used in this study (default value: IPCC [27]).

The equation for Total Nitrogen in the effluent is given by Eq. (31),

$$N_{effluent} = (P \times Protein \times F_{NPR} \times F_{NON-CON} \times F_{IND-COM}) - N_{sludge} \tag{31}$$

where $N_{effluent}$ is total annual amount of nitrogen in the wastewater effluent (kg N yr^{-1}), P is human population, protein is annual per capita protein consumption (kg person yr^{-1}), F_{NPR} is fraction of nitrogen in protein (kg N kg protein), $F_{NON\text{-}CON}$ is factor for non-consumed protein added to the wastewater, $F_{IND\text{-}COM}$ is factor for industrial and commercial co-discharged protein into the sewer system, N sludge is nitrogen removed with sludge (kg N yr^{-1}).

Per capita protein consumption (Pr) value is taken as 21.462 (Nutritional Intake in India, 2009–2010), fraction of nitrogen in protein (F_{NPR}), fraction of non-consumption protein ($F_{NON\text{-}CON}$) and fraction of industrial and commercial co-discharged protein ($F_{IND\text{-}COM}$) values are taken as 0.16 kg N/kg protein, 1.4 (fraction) and 1.25 (fraction), respectively [30].

Industrial wastewater may be treated on site by the industries or can be discharged into domestic sewer systems. The emissions are included in domestic wastewater emissions, if it is released into the domestic sewer system. Methane is produced only from industrial wastewater with significant carbon loading that is treated under intended or unintended anaerobic conditions [30]. Major industrial waste water sources having high CH_4 production potential are pulp and paper manufacture, meat and poultry industry, alcohol, beer and starch production, organic chemicals production and food and drink processing industries. In this study industrial waste water emissions are calculated based on the data availability from the industries located within the city limits. Methodology for estimation of CH_4 emissions from on-site industrial wastewater treatment is given in Eq. (32),

$$CH_4 emissions = \sum_i (TOW_i - S_i) EF_i - R_i \tag{32}$$

where CH_4 Emissions is the CH_4 emissions in inventory year (kg CH_4 yr); TOW_i is total organically degradable material in wastewater from industry; i is in inventory year (kg COD yr); i is industrial sector; S_i is organic component removed as sludge in inventory year (kg COD yr); EF_i is emission factor for industry i; kg CH_4 kg COD for treatment/discharge pathway or system(s) used in inventory year.

If more than one treatment practice is used in an industry then weighted average is taken for this factor.

R_i=amount of CH_4 recovered in inventory year, kg CH_4 yr^{-1}.

Emission factor (EF_j) for each treatment/discharge pathway or system is calculated using Eq. (33),

$$EF_j = Bo \times MCF_j \tag{33}$$

where EF_j is emission factor for each treatment/discharge pathway or system (kg CH_4 kg COD); j is each treatment/discharge pathway or system; Bo is maximum CH_4 producing capacity (kg CH_4 kg COD); MCF_j is methane correction factor (fraction).

The total amount of organically degradable material in the wastewater (TOW) is a function of industrial output (product) P (t yr^{-1}), wastewater generation W (m^3 t^{-1} of product) and degradable organics concentration in the wastewater COD (kg COD m^{-3}).

$$TOW = P \times BOD \times 0.001 \times I \times 365 \tag{34}$$

where TOW is the total organically degradable material in wastewater for industry i (kg COD yr^{-1}); i is the industrial sector; P_i is the total industrial product for industrial sector i (t yr^{-1}); W_i is the wastewater generated (m^3 $t_{product}$); COD_i is the chemical oxygen demand (kg COD m^{-3}).

4. Results and discussion

4.1. GHG emissions from energy sector

The major energy related emissions considered under this sector are emissions from electricity consumption and fugitive emissions. Emissions resulting from consumption of fossil fuels and electricity in sectors like domestic and industrial are represented independently under specific sectors respectively.

4.1.1. Electricity consumption

The major sectors for which greenhouse gases are assessed under electricity consumption are consumption in domestic sector, commercial sector, industrial sector and others (public lighting, advertisement hoardings, railways, public water works and sewerage systems, irrigation and agriculture). Emissions resulting from electricity consumption in domestic sector and industrial sectors are attributed to domestic sector along with the emissions from fuel consumption in this sector and industrial sector along with emissions occurring from industrial processes. GHG emissions from electricity consumption in commercial sector and other sectors are represented in isolation for the comparative analysis among the cities. Emissions resulting from auxiliary power consumption in plants located within the city boundary and from the supply loss is also calculated in this study. Fig. 3 illustrates the emissions resulting from electricity consumption in commercial and other sectors along with auxiliary consumption in power plants and supply losses. During the year 2009–2010, commercial sector in Delhi consumed 5339.63 MU of electricity resulting in the release of 5428.55 Gg of CO_2 equivalent emissions. The emissions hold a share of 29.66% of emissions when compared with emissions from commercial sector in other cities. Electricity consumption in other sub category which includes Delhi International Airport Limited (DIAL), Delhi Jal Board (DJB), Delhi Metro Rail Corporation (DMRC), public lighting, railway traction, agriculture and mushroom cultivation and worship/hospital consumed 2064.73 MU resulting in the emission of 2099.11 Gg of CO_2 equivalents, which is responsible for 36.51% of total emissions when compared with other cities. Auxiliary fuel consumption and supply losses resulted in 857.69 Gg of CO_2 equivalent emissions accounting for 27.07% of total emissions from this sector. CO_2 equivalent emissions from commercial, others and auxiliary consumption and supply losses along with their shares are summarized for all the cities in Table 9.

4.1.2. Fugitive emissions

The intentional or unintentional release of greenhouse gases that occurs during the extraction, production, processing or transportation of fossil fuels is known to be fugitive emissions [30]. In the present study fugitive emissions occurring from refinery crude throughput activity is estimated from Greater Mumbai city. The methane (CH_4) emissions are found to be 0.0013 Gg for the year 2009–2010 which is converted in terms of carbon dioxide (CO_2) emissions which gives a value of 0.033 Gg of CO_2 equivalents.

4.2. GHG footprint of domestic sector

Domestic sector is a major sector which contributes to the considerable amount of emissions when city level studies are carried out. The major sources include electricity consumption for lighting and other household appliances and consumption of fuel for cooking. In the present study greenhouse gases emitting from electricity consumption in domestic sector and fuel consumption are accounted. The major fuels used in this study are LPG, Piped Natural Gas (PNG) and kerosene based on the availability of data. The chart given below shows the total greenhouse gas (GHG) emissions converted in terms of CO_2 equivalent (GHG footprint/aggregated Carbon equivalent of GHG) from the domestic sector in major cities [205].

In Delhi during the study base year 2009, 11,690.43 Gg of CO_2 equivalents is emitted from the domestic sector which is the highest among all the cities that accounts for 26.4% of the total emissions when compared with other six cities (Fig. 4). Electricity consumption accounted for 9237.73 Gg of emissions out of the total domestic emissions. Earlier estimate sho an emission of 5.35 million tons (5350 Gg) of CO_2 emissions from domestic sector in Delhi during the year 2007–2008 [206]. Greater Mumbai which covers both Mumbai city and sub urban district emits 8474.32 Gg of CO_2 equivalents from the domestic sector which shares 19.14% of the total emissions. Domestic sector in Kolkata results in 6337.11 Gg of CO_2 equivalents (14.31% of total emissions). Another major city Chennai ranks second in the list with 8617.29 Gg of CO_2 equivalents, contributing to approximately 19.5% of total emissions share. Greater Bangalore accounts for an emission of 4273.81 Gg of emissions from domestic sector, 9.65% of total emissions from domestic sector. Hyderabad and Ahmedabad the other two cities are responsible for 2341.81 Gg of CO_2 equivalent and 2544.03 Gg of CO_2 equivalents, respectively. These two cities together share 11% of the total domestic emissions.

4.3. GHG footprint of transportation sector

In the major cities transportation sector is one of the major anthropogenic contributors of greenhouse gases [116]. Emissions

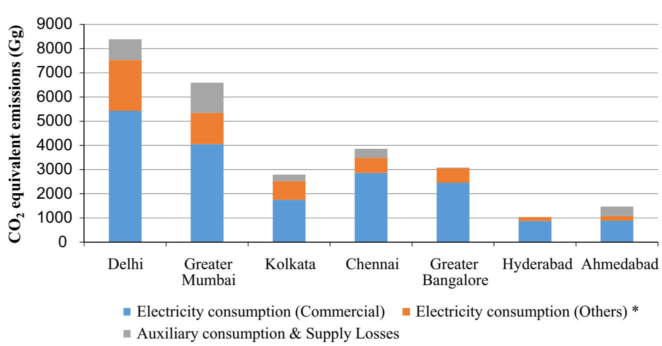

Fig. 3. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from electricity consumption.

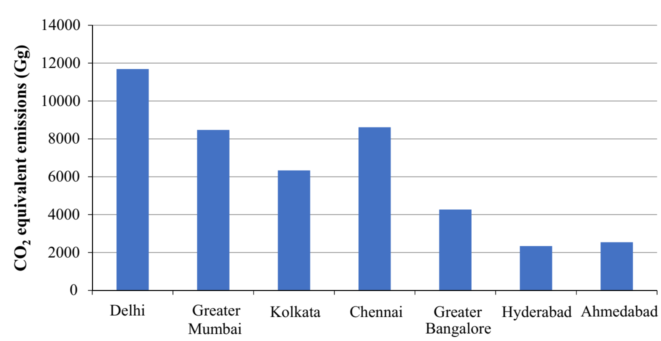

Fig. 4. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from domestic sector.

Table 9
GHG (CO_2 equivalent) emissions from electricity consumption in different cities.

Cities	CO_2 equivalent emissions from electricity consumption (Gg)					
	Commercial sector (Gg)	%	Others (Gg)[a]	%	Auxiliary consumption and supply losses (Gg)	%
Delhi	5428.55	29.66	2099.11	36.51	857.69	27.07
Greater Mumbai	4049.85	22.13	1291.49	22.46	1247.54	39.38
Kolkata	1746.34	9.54	777.46	13.52	269.43	8.50
Chennai	2859.07	15.62	624.18	10.86	375.61	11.86
Greater Bangalore	2456.80	13.43	603.46	10.50	24.85	0.78
Hyderabad	870.4	4.76	165.74	2.88	_	_
Ahmedabad	888.73	4.86	188.09	3.27	392.85	12.40

[a] Others include electricity consumption in street light, advertisement hoardings, public water works and sewerage system, irrigation and agriculture, pumping systems, religious/worship, crematorium and burial grounds.

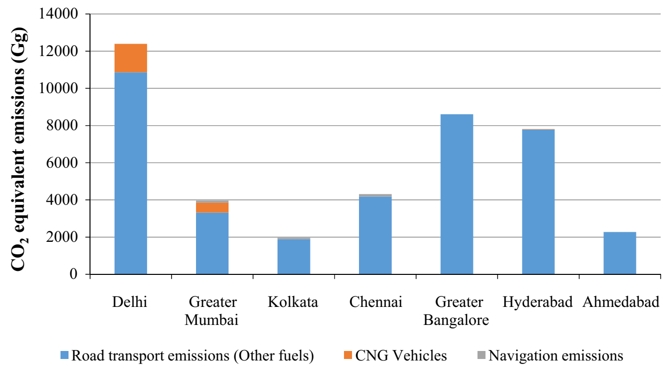

Fig. 5. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from transportation sector.

Table 10
GHG (CO_2 equivalent) emissions from transportation sector in different cities.

Cities	Road transportation emissions (Gg)		Navigation emissions (Gg)
	Vehicles using fuel other than CNG	CNG vehicles	
Delhi	10,867.51	1527.03	–
Greater Mumbai	3,320.66	531.34	114.18
Kolkata	1,886.60	–	83.06
Chennai	4,180.28	–	127.37
Greater Bangalore	8,608.00	–	–
Hyderabad	7,788.02	21.55	–
Ahmedabad	2,273.72	–	–

resulting from total vehicles registered within the city boundary and also from CNG fuelled vehicles present in few of the major cities are calculated. Navigational activities from the port cities are also included in the emissions inventory on the basis of fuel consumption. Delhi leads the emission chart among other cities due to higher emissions because of large number of vehicles. As per the statistics of Transport Department in Delhi, the total number of vehicles in Delhi is more than combined total vehicles in Mumbai, Chennai and Kolkata. Also Delhi has 85 private cars per 1000 population against 8 private cars per 1000 population on all India average. Delhi also has 344,868 CNG vehicles during the year 2009–2010 [206]. Emissions resulting from road transportation including CNG vehicles and also in port cities of India are as depicted in Fig. 5.

In Delhi during the year 2009–2010, total number of registered vehicles was 6451,883, out of which there were around 20 Lakhs of cars and jeeps and 40.5 Lakhs of motor cycles including scooters and mopeds. CNG fuelled vehicles emitted 1527.03 Gg of CO_2 equivalents whereas the remaining vehicles resulted in 10,867.51 Gg of emissions contributing almost 30% of the total emissions in this sub category which is the highest among all the major cities. This is twice the earlier estimate of 5.35 million tons (5350 Gg) of CO_2 emissions from road transportation sector in Delhi during the year 2007–2008 or emissions of 7660 Gg using top down approach or 8170 Gg using bottom-up approach [204]. The CNG vehicles are also present in two other cities: Greater Mumbai and Hyderabad. Emissions from CNG vehicles in Mumbai during the year 2009–2010 are found to be 531.34 Gg of CO_2 equivalents and for Hyderabad it is estimated that 21.55 Gg of CO_2 equivalent was emitted from CNG vehicles during the study year. The emission inventories for transportation sector in all the major cities are given in Table 10.

Table 11
GHG (CO_2 equivalent) emissions from industrial sector in different cities.

Cities	Industrial sector emissions (Gg)
Delhi	3049.30
Greater Mumbai	1798.69
Kolkata	2615.84
Chennai	4472.35
Greater Bangalore	2437.03
Hyderabad	1563.14
Ahmedabad	2044.35

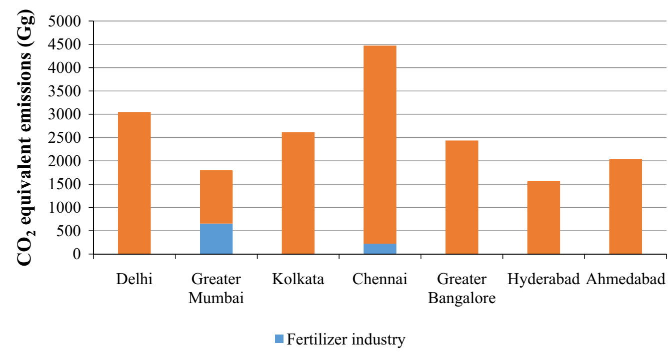

Fig. 6. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from industrial sector.

4.4. GHG footprint of industrial sector

Emissions are estimated from the major industrial processes emitting considerable greenhouse gases which are located within the city boundary (Table 11). Electricity consumption in industrial sector is taken into account using which the resulting emissions are calculated. Fuel consumption data is also used in few of the industries to estimate the emissions. Iron and steel industry, cement industry, fertilizer plants and chemical manufacturing are the few major industries which releases huge amount of greenhouse gases into the atmosphere during the process. Emissions are calculated from the major polluting industries in city boundaries as the data is not available for small and medium scale industries.

Emissions are calculated for ammonia production from the fertilizer industries in Greater Mumbai and Chennai. In Greater Mumbai during the year 2009–2010, 654.5 Gg of CO_2 equivalents are emitted from the fertilizer industry. Emissions from the fertilizer industry in Chennai are found to be 223.28 Gg of CO_2 equivalents from the production of ammonia. Emissions are also calculated from glass industries (Greater Mumbai, Greater Bangalore), paper industry (Kolkata), and petro products (Chennai) using the fuel consumption data. Though this study does not present the entire emissions across industrial sector in a city due to unavailability of data, the major greenhouse gas emitting industries are included in the study along with the electricity consumption which constitutes most of the emissions. Fig. 6 shows the emission across different cities.

4.5. GHG footprint of agricultural related activities

Methane (CH_4) emissions from paddy cultivation, nitrous oxide (N_2O) emissions from soil management are the major sectors responsible for greenhouse gas emissions from this sector. Crop residue burning is practiced in few of the Northern parts of the India which also releases GHG emissions. In the current study emission inventory is carried out from these three sectors under agriculture related activities. Table 12 shows the CO_2 equivalent emissions resulting from agriculture related activities. Fig. 7 shows

Table 12
GHG (CO_2 equivalent) emissions from agricultural related activities in different cities.

Cities	CO_2 equivalent emissions (Gg)		
	Paddy cultivation	Soils	Crop residue burning
Delhi	17.05	248.26	2.68
Greater Mumbai	–	6.95	–
Kolkata	–	10.54	–
Chennai	–	3.73	–
Greater Bangalore	5.10	113.86	–
Hyderabad	–	18.48	–
Ahmedabad	–	38.03	_

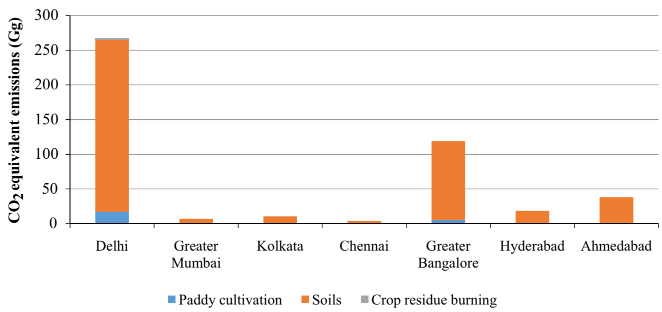

Fig. 7. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from agricultural related activities.

the pattern of carbon dioxide equivalent emissions in the major cities.

Emissions from paddy cultivation are calculated for two major cities based on the area of paddy fields. Carbon dioxide equivalents (GHG footprint) were found to be 17.05 Gg in Delhi and 5.10 Gg in Greater Bangalore, respectively. Emissions resulting from burning of crop residues at the end of growing year are estimated based on Delhi's emission of 2.68 Gg of CO_2 equivalents. N_2O emissions are converted into CO_2 equivalents as presented in Table 12. There are no agricultural activities in most of the cities which indicates decline in agricultural practices as a result of increasing urbanization.

4.6. GHG footprint of livestock management

Enteric fermentation and manure management are the two major activities resulting in the emission of greenhouse gases from animal husbandry. In the present study emissions from livestock management is carried out to calculate the emissions resulting from enteric fermentation and manure management in the major cities. Livestock population for cities is obtained for cities using 2003 and 2007 livestock census, using which the number of livestock is extrapolated to the inventory year 2009 [207,208]. The emission estimates for the major cities are as given in Table 13.

Delhi and Greater Bangalore are the major cities which emits higher amount of greenhouse gases due to animal husbandry. The emissions resulting from enteric fermentation for Delhi and Greater Bangalore are estimated to be 570.57 Gg of CO_2 equivalent and 129.36 Gg of CO_2 equivalents, respectively. Similarly Delhi and Greater Bangalore emits 43.09 Gg of CO_2 equivalent and 10.30 Gg of CO_2 equivalent respectively making these two cities higher emitters in the livestock management category among the other cities. Fig. 8 shows the emission profile of livestock management for different cities.

Table 13
GHG (CO_2 equivalent) emissions from livestock management in different cities.

Cities	CO_2 equivalent emissions from livestock management (Gg)	
	Enteric fermentation	Manure management
Delhi	570.57	43.09
Greater Mumbai	18.66	1.38
Kolkata	19.70	1.83
Chennai	7.61	0.55
Greater Bangalore	129.36	10.30
Hyderabad	41.98	3.05
Ahmedabad	93.77	6.66

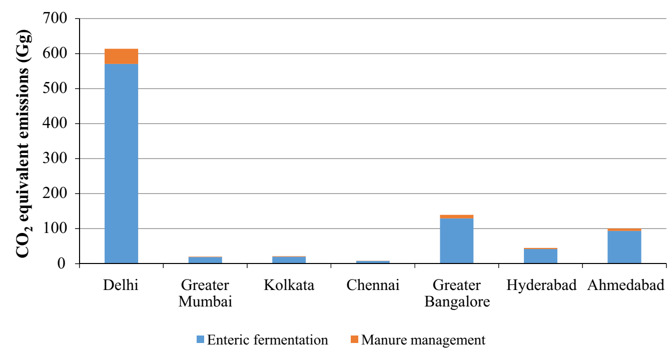

Fig. 8. GHG emissions (carbon dioxide equivalent, CO_2 eq.) from livestock management.

Table 14
GHG (CO_2 equivalent) emissions from waste sector in different cities.

Cities	CO_2 equivalent emissions from waste sector (Gg)				
	Solid waste disposal	%ge	Domestic waste water	%ge	Industrial waste water
Delhi	853.19	23.13	1378.75	28.00	–
Greater Mumbai	869.92	23.59	1058.09	21.49	–
Kolkata	535.33	14.51	385.03	7.82	143.84
Chennai	428.27	11.61	394.24	8.01	–
Greater Bangalore	374.73	10.16	759.29	15.42	–
Hyderabad	406.85	11.03	513.56	10.43	–
Ahmedabad	219.89	5.96	434.34	8.82	_

4.7. GHG footprint of waste sector

In the current study greenhouse gas emissions from 3 major waste sectors are calculated: municipal solid waste, domestic waste water and industrial waste water. CH_4 emissions from municipal solid waste disposal data are obtained from the local city municipality. CH_4 and N_2O emissions are calculated from domestic sector. In this study the industrial waste water emissions is calculated for only Kolkata city based on the availability of the data. Table 14 shows city wise CO_2 equivalent emissions and their shares in total emissions.

From the calculations of the present study Delhi emits 853.19 Gg of CO_2 equivalents and Greater Mumbai emits 869.92 Gg of CO_2 equivalent using IPCC 2006 method [30], both together is responsible for almost 46.7% of the total emissions occurring from solid waste disposal. The emissions depend on the parameters like amount of waste disposed, methane correction factor, degradable organic carbon and oxidation factor [30]. Waste disposal at cities is a major source of anthropogenic CH_4 emissions

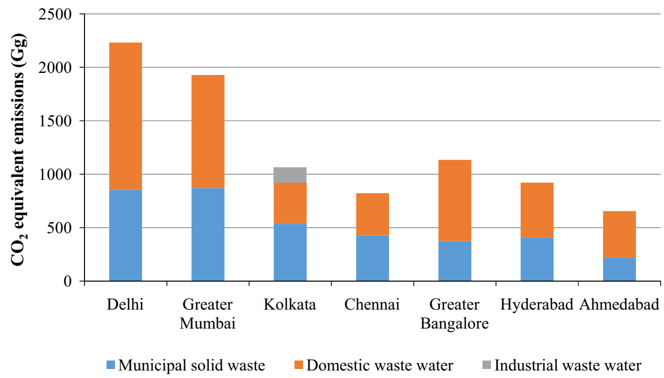

Fig. 9. Carbon dioxide equivalent emissions (CO_2 eq.) from waste sector.

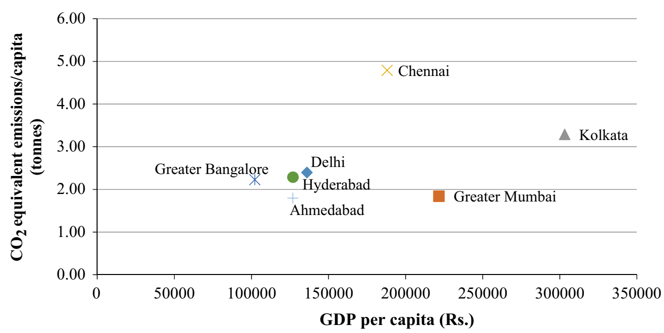

Fig. 10. CO_2 eq. emissions per capita versus GDP per capita for all the cities.

these days. CH_4 and N_2O emissions from domestic water are calculated on the basis of population of the city. From the current inventories, major emitters from domestic waste water sector are cities Delhi, Greater Mumbai and Greater Bangalore which emit 1378.75 Gg, 1058.09 Gg and 759.29 Gg of CO_2 equivalents, respectively. Emissions from industrial waste water sector in Kolkata emitted 143.84 Gg of CO_2 equivalents during 2009. Waste emission profiles for the major cities are given in Fig. 9.

4.8. GHG footprint—Intercity analyses

Economic activity is a key factor that affects greenhouse gas emissions. Increase in economy results in rise in demand for supply of energy and energy-intensive goods which will also increase the emissions. On the other hand, growth in the economy of a country results in improvement in technologies and promotes the advancement of organizations which aims at environmental protection and mitigation of emissions. In this study, total carbon dioxide equivalent emissions emitted from different major cities are compared with their economic activity, measured in terms of GDP. CO_2 equivalent emissions (GHG footprint) from Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad and Ahmedabad are found to be 38633.2 Gg, 22,783.08 Gg, 14,812.10 Gg, 22,090.55 Gg, 19,796.5 Gg, 13,734.59 Gg and 9124.45 Gg, respectively. Fig. 10 shows the relationship between carbon dioxide equivalent emissions per capita to GDP per capita.

Table 15 gives the values for carbon dioxide equivalent emissions per capita, GDP per capita and carbon dioxide equivalent emissions per GDP for the major cities.

Chennai emits 4.79 t of CO_2 equivalent emissions per capita which is the highest among all the cities, followed by Kolkata which emits 3.29 t of CO_2 equivalent emissions per capita. Chennai emits the highest CO_2 equivalent emissions per GDP (2.55 t CO_2 eq./Lakh Rs.) followed by Greater Bangalore which emits 2.18 t CO_2 eq./Lakh Rs. Fig. 11 shows the values of carbon dioxide equivalent emissions per GDP and GDP per capita for all the major cities.

Table 15
Values of CO_2 eq. emissions/capita, GDP/capita and CO_2 eq. emissions/GDP for different cities.

Cities	CO_2 eq. emissions per capita (t)	GDP per capita (Rs.)	CO_2 eq. emissions per GDP (t CO_2/Lakh Rs.)
Delhi	2.40	136,014.76	1.76
Greater Mumbai	1.84	221,608.20	0.83
Kolkata	3.29	303,187.96	1.08
Chennai	4.79	188,020.64	2.55
Greater Bangalore	2.23	102,161.49	2.18
Hyderabad	2.29	126,936.59	1.80
Ahmedabad	1.80	126,870.55	1.42

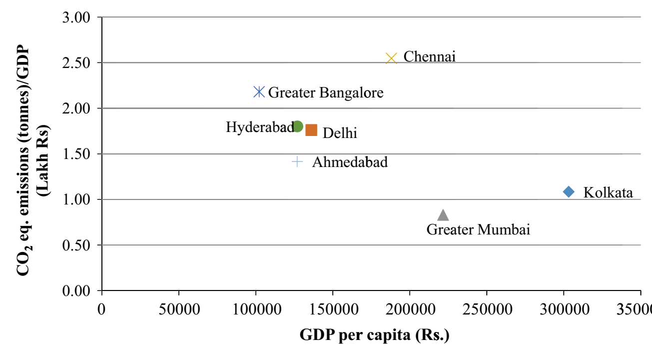

Fig. 11. CO_2 eq. emissions per GDP versus GDP per capita for all the cities.

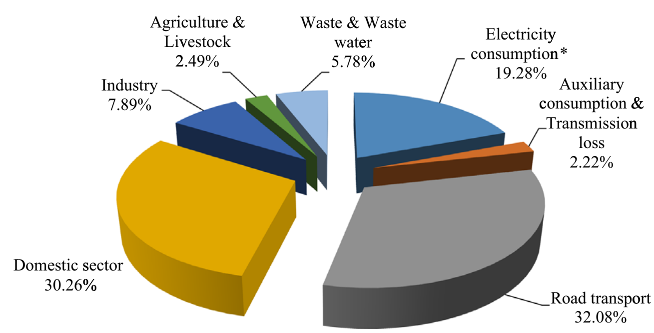

Fig. 12. GHG footprint (carbon dioxide equivalent emissions, Gg) of Delhi.

4.9. GHG footprint—City and sector

Aggregation of GHG emissions of all sectors reveal that GHG emissions in major cities in India ranges from 38,633.20 Gg year^{-1} (Delhi), 22783.08 (Greater Mumbai), 22,090.55 (Chennai), 19,796.60 (Greater Bangalore), 14,812.10 (Kolkata) to 13,734.59 (Hyderabad).

Sector wise GHG footprint analysis for Delhi city (Fig. 13) reveals that transport sector leads the carbon emission (32.08%) followed by domestic sector (30.26%) and electricity consumption (19.28%). Electricity consumption (*) includes public lighting, general purpose, temporary and colony lighting. Figs. 12–15 depicts sector-wise GHG footprint for Delhi, Mumbai, Kolkata and Chennai. In these cities domestic sector has higher GHG footprint ranging from 42.78% (Kolkata), 39.01% (Chennai) and 37.2% (Greater Mumbai). This is followed by transport sector – 19.50% (Chennai), 17.41% (Greater Mumbai), 13.3% Kolkata.

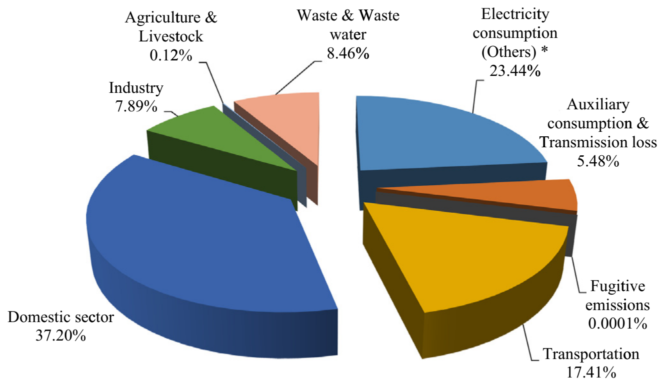

Fig. 13. GHG footprint (carbon dioxide equivalent emissions, Gg) of Greater Mumbai.

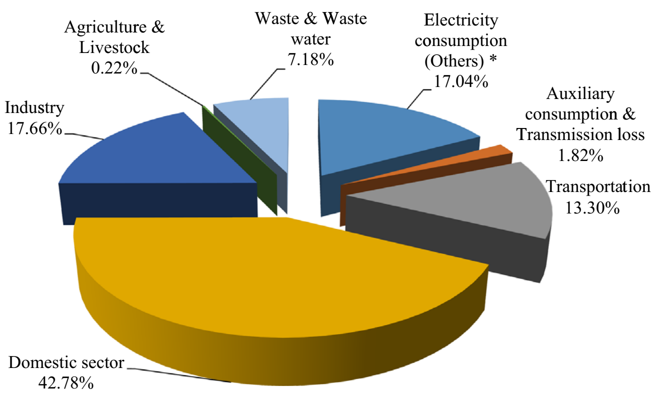

Fig. 14. GHG footprint (carbon dioxide equivalent emissions, Gg) of Kolkata.

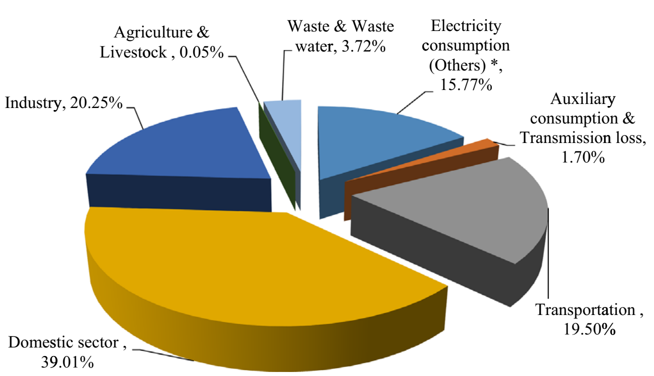

Fig. 15. GHG footprint (carbon dioxide equivalent emissions, Gg) of Chennai in 2009–2010.

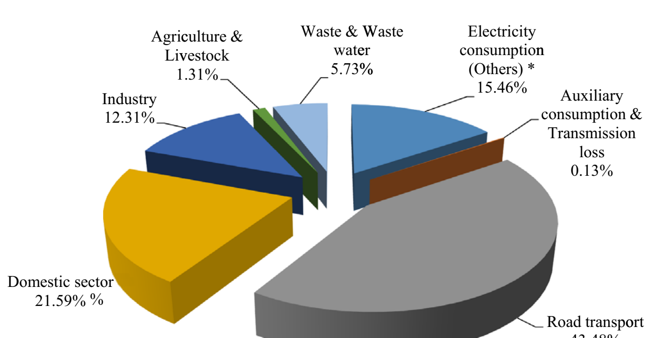

Fig. 16. GHG footprint (carbon dioxide equivalent emissions, Gg) of Greater Bangalore.

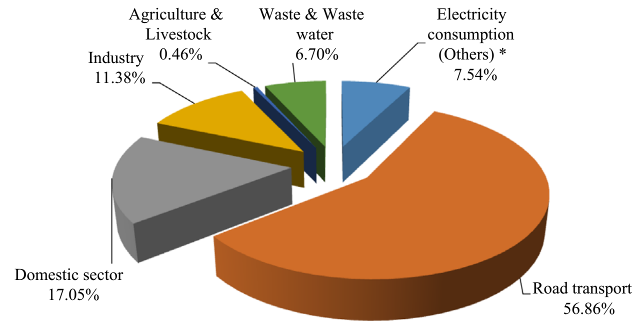

Fig. 17. GHG footprint (carbon dioxide equivalent emissions, Gg) of Hyderabad.

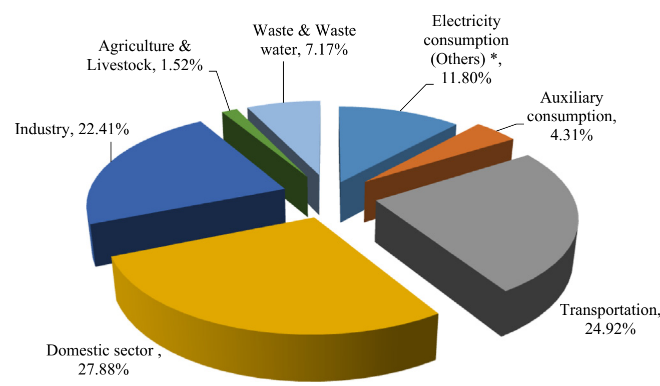

Fig. 18. GHG footprint (carbon dioxide equivalent emissions, Gg) of Ahmedabad.

Figs. 16 and 17 illustrates the sector-wise carbon emissions for IT (Information Technology) giants of India—Bangalore and Hyderabad. Due to lack of appropriate public transport system in these Cities and haphazard growth due to unplanned urbanization has led to large scale usage of private vehicles. Emissions from transport sector ranges from 43.83% (Greater Bangalore) and 56.86% (Hyderabad). Fig. 18 depicts the GHG footprint of Ahmedabad city with sector share ranging from 27.88% (Domestic), 24.92% (transportation), 22.41% (industry). etc.

5. Conclusion

India is currently second most populous country in the world and third biggest greenhouse gas emitter contributing about 5.3% of the total global emissions. Countries such as India which is one of the fast growing economies in the world, with higher energy consumption for various activities with increase in transport sector emissions with scale of rapid and uncontrolled urbanization and quest of higher living standards are eventually the causes of GHG emissions in todays' scenario. The quality of air in the major Indian cities which affects the climatic conditions as well as health of the community is a major environmental concern. Higher levels of energy consumption have contributed to the degradation of the environment. Chennai emits 4.79 t of CO_2 equivalent emissions per capita, the highest among all the cities followed by Kolkata which emits 3.29 t of CO_2 equivalent emissions per capita. Also Chennai emits the highest CO_2 equivalent emissions per GDP (2.55 t CO_2 eq./Lakh Rs.) followed by Greater Bangalore which emits 2.18 t CO_2 eq./Lakh Rs. GHG Footprint of all the major cities in India helps in improving national level emission inventories. In the last few years, the popularity of GHG Footprint has grown resulting in the major metropolitan global cities to estimate their greenhouse gas emissions and thereby framing regulations to reduce the emissions. The data regarding emissions from different sector helps the policy makers and city planners to devise mitigation strategies focusing on the particular sector which helps in improving the environmental conditions within the city. Implementation of emission reduction strategies in cities also helps in gaining carbon credits in the global markets, which has been an outcome of increased awareness about greenhouse gas emissions. GHG footprint of major cities in India sector-wise would help the planners in implementing appropriate mitigation measures.

- *Electricity consumption*: The calculation of greenhouse gas emissions from commercial and other (public lighting, advertisement hoardings, railways, public water works and sewerage systems, irrigation and agriculture) sectors shows that energy consumption in commercial sector is one of the major contributor of emissions in cities, which accounts for 15–24% of total emissions in cities, except for Hyderabad and Ahmedabad where it contributes 7.5% and 12% of the total emissions. Delhi and Greater Mumbai are the two major cities with an emission of 7448.37 Gg and 5341.34 Gg CO_2 equivalents respectively during 2009. This study also accounts for emissions from power plants located within the city. The results highlight that energy consumption in commercial sector in cities are a major source of emissions. It becomes important especially in such scenarios for adopting and using power plants that have almost zero conversion emissions based on renewable energies such as wind, solar etc.,
- *Domestic sector*: The study reveals that domestic sector causes majority of the emissions in all the major cities due to the use of fossil fuels like LPG, kerosene and PNG for cooking purposes. Fossil fuels used for cooking purposes in household's cause indoor air pollution. Consumption of electricity in domestic sector for lighting, heating and household appliances also share a major portion of emissions. It is calculated that domestic sector resulted in emissions of 11,690.43 Gg of CO_2 equivalents (∼30% of the total emissions) in Delhi which is the highest among all the cities followed by Chennai and Greater Mumbai which emits 8617.29 Gg (∼39% of total emissions) and 8474.32 Gg of CO_2 equivalents (∼39% of total emissions), respectively. GHG emissions from domestic sector in cities show the scope for cleaner fuels for cooking through the renewable sources—solar energy for water heating and other household purposes.
- *Transportation sector*: Road transport is another chief sector other than domestic sector causing major portion of emissions in the cities. From the results obtained, major emitters are Delhi and Greater Bangalore which emits 12,394.54 Gg and 8608 Gg of CO_2 equivalents, respectively. Transportation sector is a major source of emissions when city level studies are carried out. Emissions from CNG vehicles in few of the cities are calculated along with the fuel consumption for navigation in the port cities. Lesser polluting fuels like LPG and CNG can be made compulsory in major cities, phasing out older and inefficient vehicles and extensive public transport helps in reducing pollution.
- *Industrial sector*: Industrial sector contributes approximately 10–20% of the total emissions in all the major cities. In this study electricity consumption in industries is taken for all the cities and also emissions from major industries located within the city boundary. Chennai city is found to be the highest emitter, which emits 4472.35 Gg of CO_2 equivalents. There is insufficient data for medium and small scale industries located within the cities.
- *Agriculture and livestock activities*: Due to the increasing urbanization, there are not much agricultural related activities and animal husbandry practiced in the major metropolitan cities. This sector accounts less than 3% of total emissions among the cities. Delhi and Greater Bangalore emits 961 Gg and 258.6 Gg of CO_2 equivalents due to livestock management and agricultural activities. The results prove that the agricultural practices are decreasing in cities due to increase in the urban growth. There has also been suggestion that agricultural lands that are existent can be made to emit lower carbon by diversifying crop rotation systems significantly lowers GHG footprint.
- *Waste sector*: Management and treatment of solid and liquid waste in cities results in emissions. This sector shares 3–9% of total emissions resulting from the cities. Delhi and Greater Mumbai emits the major amount of emissions, 2232 Gg and 1928 Gg of CO_2 equivalents when compared with other cities. This showed that waste sector accounts for considerable amount of greenhouse gas emissions when city level studies are carried out.

Scope of further research

- Developing national level emission factors for different processes from various categories for which there are no country specific emission factors helps in improving the precision of such emission estimations. Data availability for category wise fossil fuel consumption (commercial, industrial) and for small and medium scale industries along with the waste water treatment data for different years helps in improving the values obtained from these sectors for a particular inventory year.
- Based on the results obtained, policies are to be framed focusing on reduction of emissions from the targeted sector. For example, cities with higher domestic emissions, use of cleaner fuels like LPG, PNG are to be made mandatory and also utilization of solar energy for lighting and water heating purposes. For cities with higher transportation emissions, less polluting fuels like LPG and CNG may be made compulsory in vehicles like cars, auto rickshaws and buses, introducing more public transportation services and phasing out older vehicles. This helps the local authorities in drafting regulations resulting in mitigation of environmental degradation in cities.

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