Sector-Wise Assessment of Carbon Footprint Across Major Cities in India

T. V. Ramachandra, K. Sreejith and H. A. Bharath

Abstract The concentration of greenhouse gases in the atmosphere has increased rapidly due to anthropogenic activities, resulting in a significant increase of the earth's temperature and causing global warming. These effects are quantified using an indicator such as global warming potential, expressed in units of carbon dioxide equivalent (CO_2eq), to indicate the carbon footprint of a region. Carbon footprint is thus a measure of the impact of human activities on the environment in terms of the amount of greenhouse gases produced. This chapter focuses on calculating the amount of three important greenhouses gases—carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—and thereby determining the carbon footprint of the major cities in India. National greenhouse gas inventories are used for the calculation of greenhouse gas emissions. Country-specific emission factors are used where all the emission factors are available. Default emission factors from Intergovernmental Panel on Climate Change 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. To calculate total emissions of a gas from all its source categories, emissions are summed over all source categories. The current study estimates greenhouse gas emissions (in terms of CO_2 equivalent) in major Indian cities and explores the linkages with the population and gross domestic product (GDP). Carbon dioxide equivalent emissions from Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad, and Ahmedabad were found to be 38633.2, 22783.08, 14812.10,

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T. V. Ramachandra (✉) · K. Sreejith · H. A. Bharath
Energy and Wetlands Research Group, CES TE15, Center for Ecological Sciences (CES),
Indian Institute of Science, Bangalore 560019, India
e-mail: cestvr@ces.iisc.ernet.in
URL: http://ces.iisc.ernet.in/energyhttp://ces.iisc.ernet.in/foss

T. V. Ramachandra
Centre for Sustainable Technologies (astra), Bangalore, India

T. V. Ramachandra
Centre for infrastructure, Sustainable Transportation and Urban Planning (CiSTUP),
Indian Institute of Science, Bangalore, Karnataka 560012, India

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22090.55, 19796.5, 13734.59, and 9124.45 Gg CO_2eq, respectively. The major sector-wise contributors to the total emissions in Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad, and Ahmedabad are the transportation sector (32, 17.4, 13.3, 19.5, 43.5, 56.86 and 25 %, respectively), the domestic sector (30.26, 37.2, 42.78, 39, 21.6, 17.05 and 27.9 %, respectively), and the industrial sector (7.9, 7.9, 17.66, 20.25, 12.31, 11.38 and 22.41 %, respectively). Chennai emits 4.79 tons of CO_2 equivalent emissions per capita, the highest among all the cities, followed by Kolkata, which emits 3.29 tons of CO_2 equivalent emissions per capita. Chennai also emits the highest CO_2 equivalent emissions per GDP (2.55 tons CO_2 eq/lakh Rs.), followed by Greater Bangalore, which emits 2.18 tons CO_2 eq/lakh Rs.

Keywords Carbon footprint · Domestic sector · Global warming potential · Gross domestic product · India · Industries · Major cities · Transportation

1 Introduction

Greenhouse gases are the 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 clouds (Intergovernmental Panel on Climate Change (IPCC) 2007a, b). The concentration of greenhouse gases (GHGs) in the atmosphere has increased rapidly due to anthropogenic activities, resulting in a 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. This phenomenon is known as the natural greenhouse gas effect, whereas the enhanced greenhouse effect is an added effect caused by human activities. Increases in the concentration of these greenhouse gases result in global warming. The atmospheric concentrations of GHGs have increased due to increasing emissions in the industrialization era. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the major greenhouse gases. Among the GHGs, carbon dioxide is the major contributor to global warming, accounting for nearly 77 % of the global total CO_2 equivalent GHG emissions (IPCC 2007b).

In 1958, attempts were made towards high-accuracy measurements of atmospheric CO_2 concentration to document the changing composition of the atmosphere with time series data (Keeling 1961, 1998). The increasing abundance of two other major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O), in the atmosphere have been reported (Steele 1996). Methane levels were found to increase at a rate of approximately 1 % per year in the 1980s (Graedel and McRae 1980; Fraser et al. 1981; Blake et al. 1982); however, during 1990s, its rate retarded to an average increase of 0.4 % per year (Dlugokencky et al. 1998). The increase in the concentration of N_2O is smaller, at approximately 0.25 % per year (Weiss 1981; Khalil and Rasmussen 1988). A second class of greenhouse gases—the synthetic

HFCs, PFCs, SF_6, CFCs, and halons—did not exist in the atmosphere before the twentieth century (Butler et al. 1999). CF_4, a PFC, is detected in ice cores and appears to have an extremely small natural source (Harnisch and Eisenhauer 1998).

The climate system is a complicated, inter-related system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water and living things (Le Treut et al. 2007; Bouwman 1990; Bronson et al. 1997). Climate change is a serious threat to the global community. Rising global temperatures will affect the local climatic conditions and also melt the fresh water ice glaciers, causing the sea levels to rise. There is universal scientific understanding that the earth's climate is changed by GHG emissions generated by human activity (Anthony et al. 2006). Surface air temperature is the parameter generally taken into account for climate change. Extensive studies have been carried out to study the patterns of global and regional mean temperatures with respect to time (Hasselmann 1993; Schlesinger and Ramankutty 1994; North and Kim 1995).

The atmospheric concentrations of carbon dioxide equivalents with the possibility of increases in global temperatures beyond certain levels have been reported (Stern et al. 1996). The recent (globally averaged) warming by 0.5 °C is partly attributable to such anthropogenic emissions (Anthony et al. 2006). Changes in climate also result in extreme weather events, such as 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 (Hingane et al. 1985; Kumar et al. 2000). This necessitates understanding the sources of global GHG emissions to implement appropriate mitigation measures.

Carbon Dioxide (CO_2) *Emissions*. CO_2 abundance was found to be significantly lower during the last ice age than over the last 10000 years of the Holocene per initial measurements (Delmas et al. 1980; Berner et al. 1980; Neftel 1982). CO_2 abundances ranged between 280 ± 20 ppm in the past 10000 years up to the year 1750 (Indermuhle 1999). There was an exponential increase of CO_2 abundance during the industrial era, to 367 ppm in 1999 (Neftel et al. 1985; Etheridge 1996; Houghton et al. 1992; IPCC 1996, 1998, 2000, 2001a, b) and to 379 ppm in 2005.

Methane (CH_4) *Emissions*. Anthropogenic activities such as fossil fuel production, enteric fermentation in livestock, manure management, cultivation of rice, biomass burning, and waste management release methane to the atmosphere to a significant extent. Estimates indicate that human-related activities release more than 50 % of global methane emissions (EPA 2010). Natural sources of methane include wetlands, permafrost, oceans, freshwater bodies, non-wetland soils, and other sources such as wildfires. Accelerating increases in methane and nitrous oxide concentrations were reported during the twentieth century (Machida 1995; Battle 1996). There was a constant abundance of 700 ppb until the nineteenth century. A steady increase brought methane abundances to 1745 ppb in 1998 (IPCC 2001b, 2003) and 1774 ppb in 2005 (IPCC 2006).

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 (EPA 2010). From the measurements for N_2O, it is found that the relative increase during the industrial period is smaller than for other GHGs (15 %). The analysis showed a concentration of 314 ppb in 1998 (IPCC 2001b), rising to 319 ppb in 2005.

1.1 Carbon Emissions 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 (McKinnon and Piecyk 2010; Benjamin 2009). The emission of greenhouse gases into the atmosphere has caused concern about global warming, with efforts focusing on minimizing the emissions. Heavy industries are transferred to knowledge-based and service industries, which are relatively cleaner, as economic development continues (Shafik and Bandyopadhyaya 1992). At advanced levels of growth, there was a gradual decrease of environmental degradation because of increased environmental awareness and enforcement of environmental regulation (Stern et al. 1996). There is a need for a target that aids local and national governments in framing climate change policies and regulations.

Carbon dioxide emissions and energy consumption are closely correlated with the size of a country's economy (Cook 1971; Humphrey et al. 1984; Goldemberg 1995; Benjamin 2009). Carbon intensity is one of the most important indicators to 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 a clear understanding of the impact of the factors that are responsible for emissions and also helps policy makers to formulate future energy strategies and emission reduction policies (Ying et al. 2007). The analysis of changes in carbon intensity in developing countries helps to optimize fuel-mix and economic structure; meanwhile, it also provides detailed information on mitigation in the growth of energy consumption and related CO_2 emissions.

Carbon intensity value drops if there is a decrease in emissions or sharp rise in the economic growth of a country. Carbon dioxide emissions resulting from the consumption of energy in certain countries were compiled from published literature (International Energy Statistics, United States Energy Information Administration, EIA). Economic growth data were obtained from the World Bank (http://worldbank.org). GDP in domestic currencies were converted using official exchange rates from 2,000. Figure 1 illustrates the carbon intensity trend across major carbon players. India's overall carbon intensity of energy use has marginally decreased in recent years, despite coal's dominance. Strong growth in wind capacity and efficiency improvements in coal-based electricity production are some factors that are responsible for the decline of carbon intensity (Rao and Reddy 2007; Rao et al. 2009).

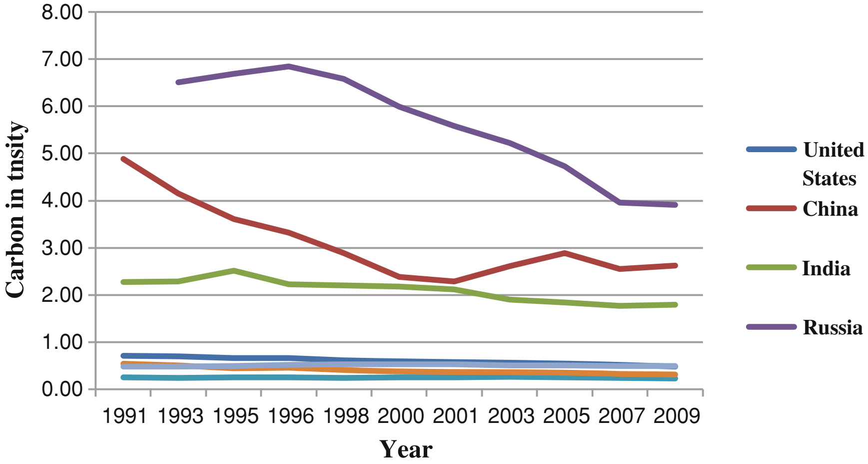

Fig. 1 Carbon intensity by country (kg CO_2/constant US $)

1.2 Carbon Footprint

Many organizations and governments are looking for strategies to reduce emissions from greenhouse gases from anthropogenic origins, which are responsible for global warming (Kennedy et al. 2009, 2010). The increasing interest in carbon footprint assessment has resulted from the growing public awareness of global warming. The global community now recognizes the need to reduce greenhouse gas emissions to mitigate climate change (Jessica 2008). Many global metropolitan cities and organizations are estimating their greenhouse gas emissions and developing strategies to reduce their emissions.

The *carbon footprint* is defined as a measure of the impact of human activities on the environment in terms of the amount of greenhouse gases produced. The total greenhouse gas emissions from various anthropogenic activities from a particular region are expressed in terms of carbon dioxide equivalent, which indicate the carbon footprint of that region (Andrew 2008). Carbon dioxide equivalent (CO_2e) is a unit for comparing the radiative forcing of a GHG (a measure of the influence of a climatic factor in changing the balance of energy radiation in the atmosphere) to that of carbon dioxide (ISO 14064-1, 2006a, b). It is the amount of carbon dioxide by weight that is emitted into the atmosphere and would produce the same estimated radiative forcing as a given weight of another radiatively active gas.

Carbon dioxide equivalents are calculated by multiplying the weight of the gas being measured by its respective global warming potential (GWP). 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 IPCC, a GWP is an indicator that reflects the relative effect of a greenhouse gas in terms of climate change over a fixed time period, such as 100 years (GWP_{100}). GWP is 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 (Matthew 1999). The GWP of major greenhouse gases over the next 20 years are 1 for CO_2, 25 for CH_4, and 298 for nitrous oxide (IPCC 2007a, b).

Need for Estimation of Carbon Footprint. Carbon footprint calculations have the potential to reduce the impact on climate change by increasing consumer awareness and fostering discussions about the environmental impacts of products. They offer valuable information for sustainable urban planning for policy makers and local municipalities (Bhatia 2008; Carbon Trust 2007a, b; Courchene and Allan 2008; Hammond 2007; Hoornweg et al. 2011; Laurence et al. 2011).

1.3 Carbon Footprint Studies in Cities

Emissions of GHG emissions at city levels with a detailed analysis of per capita GHG emissions for several large cities helps in evolving appropriate mitigation measures and resource efficiency (Hoornweg et al. 2011). Kennedy et al. (2009, 2010) developed a method for comparing emissions resulting from electricity consumption, heating and industrial fuel use, transportation, and waste sectors across 10 global cities. Similar studies by Sovacool and Brown (2009) provided a comparative account of carbon footprints in metropolitan areas, with suggestions for policymakers and planners regarding policy implications. The assessment of carbon footprint is being used for the management of climate change and to mitigate changes in climate at local levels. Studies on the carbon footprint of Norwegian municipalities were calculated to be related to the factors of size and wealth (Hogne et al. 2010).

1.4 Sector-Wise Assessment of GHG Emissions in India: Review

GHG Emissions in Electricity Generation Sector in India. GHG emissions from electricity use occur during the generation of electricity. Earlier studies have estimated the emission of gases due to power generation (Gurjar et al. 2004; Raghuvanshi et al. 2006; Chakraborty et al. 2007; Weisser 2007; Kennedy et al. 2009; Shobhakar 2009; Kennedy et al. 2010; Chun Ma et al. 2011; Qader 2009; POST 2006). 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), sulfur oxides (SOx), nitrogen oxides (NOx), other trace gases, and airborne inorganic particulates, such as fly ash and suspended particulate matter. Inventory of carbon dioxide emissions from coal-based power generation in India were carried out for the present energy generation, with projections for next two decades (Raghuvanshi et al. 2006). A comprehensive emission inventory for megacity Delhi, India for the period 1990–2000 was 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 were reported (Gurjar et al. 2004, 2010).

Measurements of CO_2 and other gases from coal-based thermal power plants in India have been reported. The emission rates of the GHGs were found to be dependent on factors such as the quality of coal mixture/oil, quantity used for per unit generation, age of the plant, and amount of excess air fed into the furnace (Chakraborty et al. 2007). A study of large point source emissions from India was carried out (Garg et al. 2001) for 1990 and 1995 using the IPCC (1996) method, indicating that CO_2 and SO_2 emissions were the major gases emitted from power plants.

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. Studies have been 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 (BSI 2008; Murthy et al. 1997a, b; Pachauri and Spreng 2002; Pachauri 2004; Parikh et al. 1997; INCCA 2010; Garg et al. 2004, 2006, 2011). 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 (INCCA 2010). A city-level emission inventory for key sectors found that the household sector was responsible for a major portion of emissions. Therefore, it is a target sector for emission reduction in both existing and new housing, in which energy efficiency is increased (Gupta et al. 2006; Reddy and Srinivas 2009).

GHG Emissions in the Transportation Sector. Emissions from the road transportation sector are directly related to gasoline and diesel consumption. Increases in emissions have been due to increases in the number of motor vehicles on the road and the distance these vehicles travel (Anil Singh et al. 2008). The traffic composition of six megacities of India (Delhi, Mumbai, Kolkata, Chennai, Bangalore, and Hyderabad) shows that there has been a significant shift from the share of slow-moving vehicles to fast-moving vehicles and public transport to private transport (Jalihal et al. 2005; Jalihal and Reddy 2006). Various studies have been carried out in India with regard to the emissions resulting from the transportation sector (Bhattacharya and Mitra 1998; Ramanathan 1975; Ramanathan and Parikh 1999; MiEF 2004). The trends of energy consumption and consequent emissions of greenhouse gases such as CO_2, $CH_{4,}$ and N_2O and ozone precursor gases such as CO, NO_x, and NMVOC in the road transport sector in India for the period from 1980 to 2000 have been studied. Efforts are being made to apportion the fuels, both diesel and gasoline, across different categories of vehicles operating on the Indian roads (Anil Singh et al. 2008; Ramachandra and Shwetmala 2009) and determine the major sources of air pollutants in urban areas (Gurjar et al. 2004; Das et al. 2004; Gurjar et al. 2010).

Emissions from vehicles have been estimated using various model calculations (Goyal and Ramakrishna 1998). Studies have calculated emissions on the basis of activity data, vehicle kilometers travelled, vehicle category, and subcategories (Ramanathan and Parikh 1999; CPCB 2007; Mittal and Sharma 2003; ALGAS 1998; ADB 2006; Baidya and Borken Kleefeld 2009). 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 (ARAI 2007). Inventory estimates for the emissions of greenhouse gases and other pollutants and effects of vehicular emission on urban air quality and human health have been studied in major urbanized cities in India (Sharma et al. 1995; Sharma and Pundir 2008; Gurjar et al. 2004; Ghose et al. 2004; Ravindra et al. 2006; Jalihal and Reddy 2006).

GHG Emissions in the Industrial Sector. Industry is a major source of global GHG emissions. The industrial sector is responsible for approximately one-third of global carbon dioxide emissions through energy use (William 1996). In India, emission estimates from large point sources, such as thermal power, steel industry, cement plants, chemical production and other industries, have been carried out by various researchers (Mitra 1992; Mitra et al. 1999a, b; Garg et al. 2001, 2004; Mitra and Bhattacharya 2002; Gurjar et al. 2004; Garg et al. 2006). CO_2 emissions from iron and steel, cement, fertilizer, and other industries such as lime production, ferroalloy production, and aluminum production have been estimated (Garg et al. 2006, 2011).

Six industries in India have been identified as energy-intensive industries: aluminum, cement, fertilizer, iron and steel, glass, and paper manufacturing. The cement sector holds a considerable share within these energy-intensive industries (Schumacher and Sathaye 1999; Bernstein et al. 2007). At the country level, trends of GHG emissions from industrial processes indicated 24,510 CO_2 equivalent emissions in the year 1990, 102,710 CO_2 equivalent emissions in 1994, 168,378 CO_2 equivalent emissions in 2000 and 189,987.86 CO_2 equivalent emissions in 2007 (Sharma et al. 2009, 2011; Kumar 2003). 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 (Sharma et al. 2011).

GHG Emissions in Agriculture Sector. Agricultural activities contribute directly to emissions of GHGs through a variety of processes. The major agricultural sources of GHGs are methane emissions from irrigated rice production, nitrous oxide emissions from the use of nitrogenous fertilizers, and the release of carbon dioxide from energy sources used to pump groundwater for irrigation (Nelson et al. 2009). 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 and domestic biofuel; the remainder is burnt in the field

(Reddy et al. 2002). Rice paddy soils contain organic substrates, nutrients, and water; therefore, they are an increasing source of methane resulting from the anaerobic decomposition of carbonaceous substances (Alexander 1961). The anaerobic bacterial processes in the irrigated rice cultivated fields are considered to be among the largest sources of methane emission (Sass and Fisher 1998); the annual global contribution of methane is estimated to be $\sim$190 Tgy^{-1} (Koyama 1963; Yanyu et al. 2006).

Studies on CH_4 emission from Indian rice fields have been carried out by different researchers to study the effects of soil type, season, water regime, organic and inorganic amendments, and cultivars (Parashar et al. 1991; Mitra 1992; Parashar et al. 1993, 1994; Adhya et al. 1994; Sinha 1995; Mitra et al. 1999a, b; Chakraborty et al. 2000, 2007; Jain et al. 2000; Khosa et al. 2010). Average methane flux varied significantly with different cultivars, ranging between 0.65 and 1.12 mg m^{-2} h^{-1} (Mitra et al. 1999a, b). CH_4 emissions from Indian rice paddies, therefore, is estimated to be 3.6 ± 1.4 Tg y^{-1}, which is lower than the value of 4.2 (1.3 to 5.1) Tg y^{-1} obtained using the IPCC 1996 default emission factors (Gupta et al. 2009). India emitted 3.3 million tons of CH_4 in 2007 from 43.62 million ha cultivated (Gupta 2005; MoA 2008; INCCA 2010). The application of nitrogen fertilizer in upland irrigated rice has led to increased N_2O emissions (Kumar et al. 2000; Majumdar et al. 2000; Ghosh et al. 2003; Garg et al. 2004, 2006). Total seasonal N_2O emission from different treatments ranged from 0.037 to 0.186 kg ha^{-1} (Ghosh et al. 2003; Aggarwal et al. 2003; Bhatia et al. 2008; Bhatia 2008; INCCA 2010).

GHG Emissions in the Livestock Sector. There are two major sources of methane emission from livestock: enteric fermentation resulting from digestive process of ruminants and animal waste management (IPCC 2006; Bandyopadhyay et al. 1996). Animal husbandry accounts for 18 % of GHG emissions that cause global warming (Naqvi and Sejian 2011). Methane emission from enteric fermentation from Indian livestock ranged from 7.26 to 10.4 MT/year (Garg and Shukla 2002). In India, more than 90 % of the total methane emission from enteric fermentation is contributed by large ruminants (cattle and buffalo), with the rest from small ruminants and other animals (Swamy and Bhattacharya 2006). The 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 such as sunlight, temperature, precipitation, wind, etc. (Gaur et al. 1984; Yamulki et al. 1999).

In India, studies have been carried out in which the emission inventories for enteric fermentation and manure management were done at the national level (Garg et al. 2001; Naqvi and Sejian 2011; Gurjar et al. 2004, 2009; Garg et al. 2011). The total emission of methane from Indian livestock was estimated to be 10.08 MT, considering different categories of ruminants and type of feed resources available in different zones of the country (Singhal et al. 2005). 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 be approximately 698 ± 27 Gg CH_4 from all manure management systems and 2.3 ± 0.46 tons of N_2O from solid storage of manure for the year 2000 (Gupta et al. 2009). Using the emission factors provided in the report (NATCOM 2004), it is estimated that the Indian livestock emitted 9.65 million tons in 2007. Buffalo are the single largest emitter of CH_4, constituting 60 % of the total CH_4 emission from this category, simply because of their large numbers compared to any other livestock species and also because of the large CH_4 emission factor with respect to others (INCCA 2010). By using the IPCC guidelines, the total CH_4 emitted from enteric fermentation in livestock was found to be 10.09 million tons; emissions from manure management were estimated to be approximately 0.115 million tons of CH_4 and 0.07 thousand tons of N_2O (INCCA 2010).

GHG Emissions Inventory in the Waste Sector. The main GHG emitted from waste management is CH_4. It is produced and released into the atmosphere as a byproduct of the anaerobic decomposition of solid waste, whereby 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 due to the protein content in domestically generated wastewater (INCCA 2010; Hogne et al. 2010; Marlies et al. 2009). Industrial wastewater with significant carbon loading that is treated under intended or unintended anaerobic conditions will produce CH_4 (IPCC 2006).

Waste landfills are considered to be the largest source of anthropogenic emissions. Methane emissions from landfills are estimated to account for 3–19 % of the anthropogenic sources in the world (IPCC 1996). Landfill gas, primarily a mix of CO_2 and CH_4, is emitted as a result of the restricted availability of oxygen during the decomposition of the organic fraction of waste in landfills (Talyan et al. 2007). Methane emissions have been estimated for specific particular landfill sites and regions in India (Kumar et al. 2000, 2004, 2009; Gurjar et al. 2004; Ramachandra and Bachamanda 2007; Subhasish et al. 2009; Rawat and Ramanathan 2011).

CH_4 emission estimates were found to be approximately 0.12 Gg in Chennai from municipal solid waste management for the year 2000, which is lower than the IPCC (1996) values.

Municipal solid waste (MSW) management in major cities in India has been assessed; parameters such as waste quantity generated, waste generation rate, physical composition, and characterization of MSW in each of the cities are carried out (Kumar et al. 2009). Solid waste generated in Indian cities increased from 6 Tg in 1947 to 48 Tg in 1997 (Pachauri and Sridharan 1998), with a per capita increase of 1–1.33 % per year (Rao and Shantaram 2003). Per INCCA (2010), 604.51 Gg of CH_4 was emitted from solid waste disposal sites in India.

Methane is generated from domestic and industrial wastewater. The main factor in determining the extent of CH_4 production is the amount of degradable organic fraction in the wastewater (Fadel and Massoud 2001), which is commonly expressed in terms of biochemical oxygen demand (BOD) or chemical oxygen demand (COD). The disposal and treatment of industrial waste and MSW are not a prominent source of methane emissions in India, except in large urban centers. In India, methane emissions from domestic/commercial and industrial wastewater were found to be 861 and 1050 Gg, respectively, for the year 2007. Approximately

15.81 Gg of nitrous oxide is emitted from the domestic/commercial wastewater sector (Garg et al. 2001; Sharma et al. 2011).

A sector-wise review highlights the fragmented efforts of assessing the carbon footprint in India. There are no comprehensive efforts to assess the carbon footprint among all sectors in rapidly urbanizing cities, which is vital for evolving appropriate city-specific mitigation measures. The objectives of this chapter are to quantify and analyze sector-wise greenhouse gas emissions in terms of carbon dioxide equivalent (CO_2 eq) across major cities in India.

Section 2 presents methods for quantifying the carbon footprint for electricity, domestic, industry, transportation, agriculture, livestock, and waste sectors; it also provides a brief account of cities chosen for the current study. Section 3 provides a detailed account of sector-wise carbon footprints for major cities in India, with a synthesis of intercity variations. This is followed by conclusions and gaps in the current study in Sects. 4 and 5, respectively. Annex 1 provides the sector-wise carbon footprints for major cities in India.

2 Method

2.1 Study Area

Carbon footprint has been assessed for eight major metropolitan cities (populations of >4 million per 2011 census) in India: Delhi, Greater Mumbai, Kolkata, Chennai, Greater Bangalore, Hyderabad, and Ahmedabad. Except for Ahmedabad, all of these cities are class X (formerly class A1) cities as per the classification of Ministry of Finance (HRA 2008). Table 1 lists the location, population, and GDP for all chosen cities. Geographic locations of the cities are depicted in Fig. 2.

Delhi. Delhi is the capital of India with long history, covering an area of 1483 km^2 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 such as power, telecommunications, health services, construction, and real estate (SOE 2010).

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. The Greater Mumbai region consists of the Mumbai city district and Mumbai suburban district. It covers a total area of 603.4 km^2, with a population of 12,376,805 (in 2009). It is also the commercial and entertainment capital of India, generating a GDP of Rs. 274,280 crores at constant prices and contributing to 5 % of India's GDP (MoUD 2009; MMRDA 2008).

Kolkata (*Calcutta*). Kolkata, the capital of West Bengal, is located on the east bank of the Hooghly River. The Municipal Corporation of Kolkata covers an area of 187 km^2, with a population of 4,503,787 (in 2009). The GDP of Kolkata in the

Table 1 Locations, populations, and GDPs 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	219360.35
Greater Mumbai	18.9° N and 72.8° E	12,376,805	274280.15
Kolkata	22°34’ N and 88°24’ E	4,503,787	136549.41
Chennai	13°04’ N and 80°17’ E	4,611,564	86706.92
Greater Bangalore	12°59’ N and 77°37’ E	8,881,631	90736.07
Hyderabad	17°28’ N and 78°27’ E	6,007,259	76254.10
Ahmedabad	23.02° N and 72.35° E	5,080,596	64457.80

Sources [a] Balachandran et al. (2000); Srivastava et al. (2007); Gupta et al. (2006, 2007, 2009); Ramachandra and Kumar (2010); Latha et al. (2003); Bhaskar et al. (2010)

[b] Population for the year 2009 was estimated using the 2001 and 2011 Census of India

[c] Pricewaterhouse Coopers study 2009

year 2009 was estimated to be Rs. 136,549 crores at constant prices, resulting in the city being a major commercial and financial hub in Eastern and Northeastern India.

Chennai (*Madras*). Chennai, the capital of the state of Tamil Nadu, is located on the Coromandel Coast of the Bay of Bengal. It had a population of 4,611,564 in the year 2009, with an area of 174 km^2, which is expanded to 426 km^2 by the city corporation in the year 2011. The economy of the city mainly depends on sectors such as automobile, software services, health care industries, and hardware manufacturing, resulting in an estimated GDP of Rs. 86,706 crores at constant prices during the year 2009 (Loganathan et al. 2011).

Greater Bangalore. Greater Bangalore is the principal administrative, cultural, commercial, and knowledge capital of the state Karnataka. It covers an area of 741 km^2 and had an estimated population of 8,881,631 in 2009. During the year 2009, Bangalore’s economy of Rs. 90,736 crores at constant prices made it one of the major economic centers in India. The city’s economy depends on information technology, manufacturing industries, biotechnology, and aerospace and aviation industries (Ramachandra et al. 2012).

Hyderabad. Hyderabad, the capital of Andhra Pradesh, is located at the north part of the Deccan plateau, with a population of 6,007,259. The municipal Corporation of Hyderabad covers an area of 179 km^2, whereas Greater Hyderabad is spread over an area of 650 km^2. The city’s economic sector depends on traditional manufacturing, knowledge, and tourism, resulting in a GDP of Rs. 76,254 crores at constant prices in the year 2009.

Ahmedabad. Ahmedabad, an industrial city, is situated on the banks of Sabarmati River in north-central Gujarat. It covers an area of 205 km^2, with a population of 5,080,596 in the year 2009. Ahmedabad is the second largest industrial center in western India after Mumbai. Automobiles, textiles, pharmaceuticals, and real estate are the major sectors contributing to the economy, which was Rs. 64,457 crores at constant prices in the year 2009.

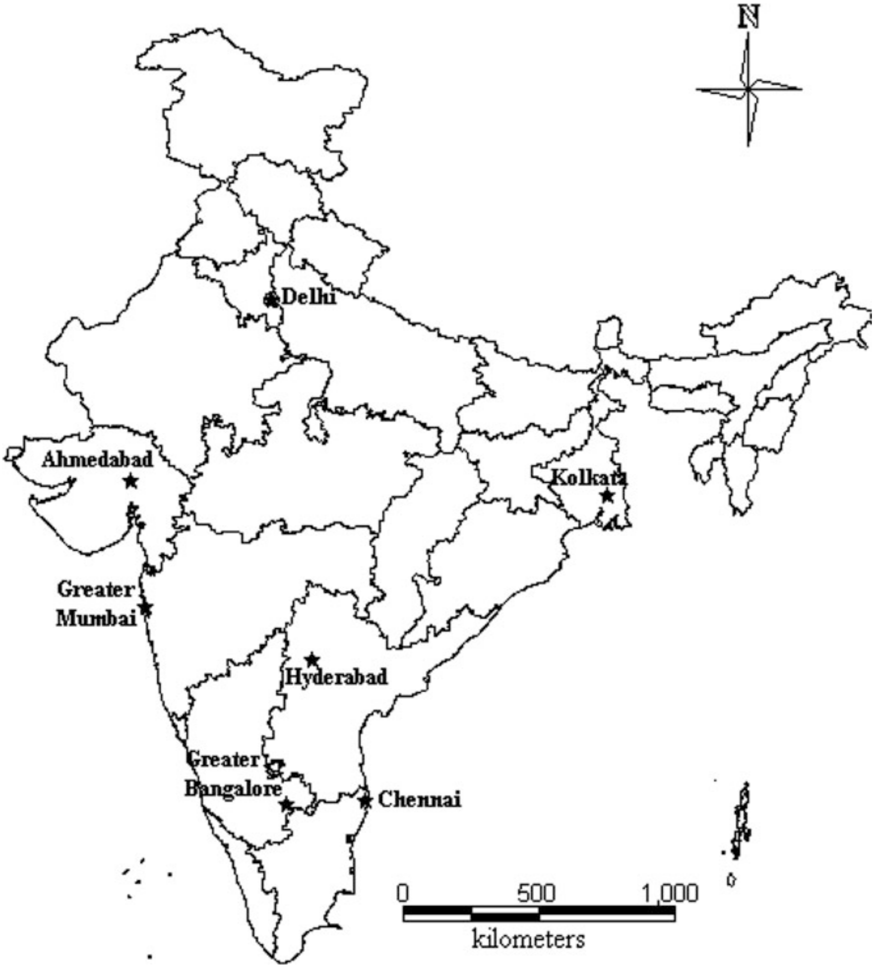

Fig. 2 Study area, indicating the major cities in India. *Source* Energy and Wetlands Research Group, Centre For Ecological Sciences, Indian Institute of Science

2.2 Quantification of Greenhouse Gases

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 GWPs. The total units of CO_2e then represent a sum total of the GWP of all three major greenhouse gases. The categories considered for GHG emission inventory are the following:

(i) Energy: electricity consumption, fugitive emissions
(ii) Domestic or household sector
(iii) Transportation

(iv) Industrial sector
(v) Agriculture-related activities
(vi) Livestock management
(vii) Waste sector.

National GHG inventories compiled from various sources were used for the calculation of GHG emissions. Country-specific emission factors were compiled from the published literature. In the absence of country-specific emission factors, the default emission factors from the IPCC were used. The emission of each GHG was estimated by multiplying fuel consumption by the corresponding emission factor. The total emissions of a gas from all its source categories (Ramachandra and Shwetmala 2012; Pandey et al. 2011; Global Footprint Network 2007) are summed as given in Eq. 1:

$$\mathrm{Emissions}_{\mathrm{Gas}} = \sum\nolimits_{\mathrm{Category}} A \times \mathrm{EF} \tag{1}$$

where

$\mathrm{Emissions}_{\mathrm{Gas}}$	emissions of a given gas from all its source categories
A	amount of an individual source category utilized that generates emissions of the gas under consideration
EF	emission factor of a given gas type by type of source category

GHG Emissions from Electricity Consumption. The combustion of fossil fuels in thermal power plants during electricity generation results in the emission of GHG into the atmosphere. CO_2, oxides of sulfur (SOx), nitrogen oxides (NOx), other trace gases, and airborne inorganic particulates, such as fly ash and suspended particulate matter, are the most important constituents emitted from the burning of fossil fuels from thermal power plants (Raghuvanshi et al. 2006; Ramachandra and Shwetmala 2012; TEDDY 2006, 2011). The emissions were computed based on consumption in the following categories: domestic, commercial, industrial, and others (which includes consumption in railways, street lights, municipal water supply, sewage treatment, etc.) based on the amount of electricity consumed by these sectors. The total GHG emissions were calculated on the basis of fuel consumption required for the generation of electricity using Eq. 2:

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

Electricity is generated from various sources (coal, hydro, nuclear, gas, etc.). The proportion of electricity generated from each source for each study region was compiled from secondary sources (state electricity board, central electrical authority, etc.). The 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

Table 2 Net calorific values and CO_2, CH_4, and N_2O emission factors for different fuel

Fuel	NCV (TJ/kt)	CO_2 EF (t/TJ)[a, b]	CH_4 EF (t/TJ)[b]	N_2O EF (t/TJ)[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
Low-sulfur heavy stock	40.19	73.3	0.003	0.0006
Residual fuel oil	40.4	77.4	0.003	0.0006
Low-sulfur fuel Oil	41	73.3	0.003	0.0006
Heavy fuel oil	40.2	73.3	0.003	0.0006

Note NCV Net Calorific Value, *EF* Emission factor

Sources [a] Indian Network for Climate Change Assessment (INCCA 2010)

[b] 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006), TEDDY (2006, 2011)

electricity (e.g., 0.7 kg coal is required for the generation of 1 unit [KWh] of electricity). The data related to electricity consumption in different cities was taken from the respective electricity boards providing electricity to that city. Table 2 lists the emission factors and the net calorific values (NCVs) of respective fuels. The total emissions obtained from the amount of fuel consumed is then distributed into major sectors, such as 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, the fuel consumption and the emissions resulting thereby were also determined for the auxiliary consumption in the power plants located within the city boundaries and the transmission loss resulting from these power plants.

Fugitive Emissions. Fugitive emissions are the intentional or unintentional release of GHGs 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 sources of CH_4 emission (INCCA 2010; Ramachandra and Shwetmala 2012). 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 are calculated from the refineries present within city boundaries, per Eq. 3:

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

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

GHG Emissions from the Domestic Sector. The large demand for energy consumption in the domestic sector is predominantly due to activities such as cooking,

Table 3 Net calorific values (NCV) and CO_2, CH_4 and N_2O emission factors for domestic fuels used in the study

Fuel	NCV (TJ/kt)	CO_2 EF (t/TJ)[a, b]	CH_4 EF (t/TJ)[b]	N_2O EF (t/TJ)[b]
Liquefied petroleum gas	47.3	63.1	0.005	0.0001
Piped natural gas	48	56.1	0.005	0.0001
Kerosene	43.8	71.9	0.01	0.0006

Note EF emission factor

Source [a] Indian Network for Climate Change Assessment (2010)

[b] 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006)

lighting, heating, and household appliances. Per the Census of India (2001), in urban areas, the most commonly used fuel is liquefied petroleum gas (LPG; 47.96 %), followed by firewood (22.74 %) and kerosene (19.16 %). Electricity consumption is another major source of energy utilization in urban households. The pollution caused by domestic fuel use is a major source of emissions in cities, which causes indoor air pollution that contributes to overall pollution. The type of fuels used in households also affects air pollution.

The emissions resulting from electricity consumption in the domestic sector are attributed to this sector. GHG emissions from fuel consumption in the domestic sector can be calculated by Eq. 4 (Ramachandra and Shwetmala 2012).

$$\begin{aligned}\text{Emissions (t)} = {} & \text{Fuel consumption (kt)} \times \text{Net calorific value of fuel (TJ/kt)} \\ & \times \text{Emission factor (t/TJ)}\end{aligned} \tag{4}$$

Table 3 lists the NCVs and emission factors for domestic fuels.

GHG Emissions from the Transportation Sector. The transportation sector is one of the dominant anthropogenic sources of GHG emissions (Mitra and Sharma 2002). The urban population predominantly depends on road transportation; therefore, there is an increase in sales of vehicles in urban areas every year. The 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 (Ramachandra and Shwetmala 2009, 2012). Emissions are estimated from either the fuel consumed (fuel sold data) or the distance travelled by vehicles. A bottom-up approach was implemented based on the number of registered vehicles, annual vehicle kilometers travelled, and corresponding emission factors for the estimation of gases from the road transportation sector (Gurjar et al. 2004; Ramachandra and Shwetmala 2009). In national-level studies, the fuel consumption approach has been used to calculate the emissions from road transport (Sikdar and Singh 2009; INCCA 2010).

A bottom-up approach was used in this study. Emissions were calculated using the data available on number of vehicles, distance travelled in a year, and the

Table 4 CO_2, CH_4, and N_2O emission factors (EFs) for different types of vehicles

Type of Vehicle	CO_2 EF (g/km)[a]	CH_4 EF (g/km)[b]	N_2O EF (g/km)[b]
Motorcycles, scooters, and 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

Sources [a] Emission factor development for Indian Vehicles, ARAI (2007)
[b] *EEA* European Environmental Agency (2009), Gurjar et al. 2004

respective emission factor for different vehicles. Emissions from road transportation were calculated per Eq. 5:

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

where

E_i	Emission of the compound (i)
Veh_j	Number of vehicles per type (j)
D_j	Distance travelled in a year per different vehicle type (j)
$E_{i,j,\mathrm{km}}$	Emission of compound (i) for vehicle type (j) per driven kilometer

Emission factors are listed in Table 4.

In this study, the number of registered vehicles in inventory year 2009 was taken from the Motor Transport Statistics of the respective states and also from the Road Transport Year Book (2007–2009) when the city-level data were not available from the local transport authorities. The Supreme Court passed an order in July 1998 to convert all public transport vehicles to compressed natural gas (CNG) mode in Delhi, which marked the beginning of CNG vehicles in India (Sandhya Wakdikar 2002; Chelani and Sukumar 2007). Emissions from the number of vehicles using CNG as a fuel were also calculated in the major cities where CNG was introduced to mitigate the emissions resulting from transportation. The vehicle kilometer travelled per year values were taken from the Central Pollution Control Board of India (CPCB 2007; Chelani and Sukumar 2007). The annual average mileage values of different vehicles used are given in Table 5.

GHG emissions for the major cities in India were calculated considering the fuel consumption for navigation in the major ports of Mumbai, Kolkata, and Chennai. The 2006 IPCC guidelines provide a method to calculate emissions from navigation (IPCC 2006). Using the ship type in the ports and gross registered tonnage (GRT), the total fuel consumed is calculated, from which the emissions are calculated. The type of ships and GRT data are available from Basis Ports

Table 5 Vehicle kilometers travelled (VKT)

Types of vehicles	VKT
Motorcycles, scooters, and 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	5,000

Source Transport fuel quality for the year 2005 from CPCB (2007)

Statistics of India (2009–10). Equation 6 was used to compute the emissions using the fuel consumption in different ship types using GRT and the ship type data as given below,

$$\begin{aligned}\text{Emissions (t)} = {} & \text{Fuel consumption (kt)} \times \text{Net calorific value of fuel (TJ/kt)} \\ & \times \text{Emission factor (t/TJ)}\end{aligned} \tag{6}$$

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 (Ramachandra and Shwetmala 2009). 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 and 74.1 t/TJ, respectively. CH_4 and N_2O emission factors are taken as 0.007 and 0.002 t/TJ, respectively, for navigation (IPCC 2006). At the country level, the emissions from shipping were calculated using the fuel consumption data (NATCOM 2004; Garg et al. 2006; Ramachandra and Shwetmala 2009; MCI 2008).

GHG Emissions from the Industry Sector. GHG 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 that release a considerable amount of CO_2 (IPCC 2006). There are no data available for the calculation of emissions from small- and medium-scale industries, which number in the thousands in major cities. In this study, the emissions were calculated from the major polluting industrial processes in the industries that are located within city boundaries. In cities such as Mumbai, the

Table 6 Values used to calculate GHG emissions from the fertilizer industry

Parameter	FR (GJ/tone NH_3 produced)	CCF (kg C/GJ)	COF (fraction)
Value	37.5	15.30	1

Source 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006)

presence of large petrochemical plants, fertilizer plants, and power plants leads to emissions (Kulkarni et al. 2000).

The GHGs estimated for the type of industries located within 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, in paper pulping, and in the manufacture of chemicals (IPCC 2006). Ammonia production data were obtained from the fertilizer industry (RCF 2010; MFL 2010); emission factors and other parameters (Table 6) were obtained from (IPCC 2006) guidelines. Emissions from ammonia production were calculated by Eq. 7.

$$E_{CO_2} = \text{AP} \times \text{FR} \times \text{CCF} \times \text{COF} \times 44/12 - R_{CO2} \tag{7}$$

where

E_{CO_2}	emissions of CO_2 (kg)
AP	ammonia production (tons)
FR	fuel requirement per unit of output (GJ/ton ammonia produced)
CCF	carbon content factor of the fuel (kg C/GJ)
COF	carbon oxidation factor of the fuel (fraction)
R_{CO2}	CO_2 recovered for downstream use (urea production) in kilograms

The glass industry can be divided into four major groups: containers, flat (window) glass, fiberglass, and specialty glass. Limestone ($CaCO_3$), dolomite Ca, $Mg(CO_3)_2$, and soda ash (Na_2CO_3) are the major glass raw materials that are responsible for the emission of CO_2 during the melting process (IPCC 2006). Equation 8 is used when there are no data available on glass manufactured by process or the carbonate used in the manufacturing of glass.

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

where

CO_2 emissions	emissions of CO_2 from glass production (tons)
Mg	mass of the glass produced (tons)
EF	default emission factor for the manufacturing of glass (tons CO_2/tons glass)
CR	cullet ratio for the process (fraction)

Table 7 gives the values of the different parameters that are used to calculate GHG emissions from the glass industry. In the present study, fuel consumption data from major industries within the city boundaries are used to calculate the

Table 7 Values used to calculate GHG emissions from the glass industry

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

Source 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006)

emissions where all data are available (annual reports of Vitrum Glass 2010; G-P (I) Ltd. 2010; EMAMI 2010; Kesoram Ind. Ltd 2010; TN Petro Products Limited 2010; Khoday India Limited 2010). The fuel consumption by industry for the year 2009–10 was obtained from the companies' annual reports, from which emissions were calculated by accounting for fuel utilization.

GHG Emissions from Agriculture-Related Activities. Agriculture-related activities, such as paddy cultivation, agricultural soils, and the burning of crop residue, are considered in the quantification of GHG emissions. Flooded rice fields are one source of methane emissions. During the paddy growing season, methane is produced from the anaerobic decomposition of organic material in flooded rice fields, which escapes to the atmosphere through rice plants by the mechanism of diffusive transport (IPCC 1997). Oxygen supply is seized from the atmosphere to the soil due to the flooding of rice fields, which leads to anaerobic fermentation of organic matter in the soil, resulting in the production of methane (Ferry 1992).

There are three processes of methane release into the atmosphere from paddy fields. The major phenomenon is CH_4 transport through rice plants (Seiler et al. 1984; Schutz et al. 1989). This accounts for more than 90 % of 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 (IPCC 1997). The emission of methane from rice fields depends on various factors, such as the amendment of organic and inorganic fertilizers, characteristics of the rice varieties, water management, and the soil environment (Mitra et al. 1999a, b). 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 subunit of harvested area, which was calculated using Eq. 9 (IPCC 2000):

$$\mathrm{CH}_{4\mathrm{Rice}} = \sum\nolimits_{i,j,k} \left(\mathrm{EF}_{i,j,k} \times A_{i,j,k} \times 10^{-6}\right) \tag{9}$$

where

$CH_{4\ \mathrm{Rice}}$	annual methane emissions from rice cultivation (Gg CH_4 year^{-1})
$EF_{i,j,k}$	seasonal integrated emission factor for i, j, and k conditions (kg CH_4 ha^{-1})
$A_{i,j,k}$	annual harvested area of rice for i, j, and k conditions (ha year^{-1})
i, j, and k	represent different ecosystems, water regimes, types and amounts 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. For studies at city levels, Eq. 10, from the revised (IPCC 1996) guidelines, was used (IPCC 1997).

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

where

Fc	estimated annual emission of methane from a particular rice water regime and for a given organic amendment (Gg/year)
EF	methane emission factor integrated over the integrated cropping season (g/m^2)
A	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/year)

This method was used because the area of paddy fields based on the type of ecosystem (irrigated, rain fed, deep water, and upland) is not available at the city level. A seasonally integrated emission factor of 10 g/m^2 was used, as obtained from the revised 1996 IPCC guidelines (IPCC 1997).

Agricultural soils contribute to the emission of two 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 byproduct of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. This method therefore estimates N_2O emissions using human-induced net nitrogen (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 (IPCC 2006; Granli and Bockman 1994).

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 NOx 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 the following equation:

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

Direct N_2O emissions. The sources included for the 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	annual direct N_2O–N emissions from managed soils (kg N_2O–N year^{-1})
N_2O–N $_{N\ Input}$	annual direct N_2O–N emissions from N inputs to managed soils (kg N_2O–N year^{-1})
N_2O–N $_{OS}$	annual direct N_2O–N emissions from managed organic soils (kg N_2O–N year^{-1})
N_2O–N $_{PRP}$	annual direct N_2O–N emissions from urine and dung inputs to grazed soils (kg N_2O–N year^{-1})

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

where

F_{SN}	annual amount of synthetic fertilizer N applied to soils (kg N year^{-1})
F_{ON}	annual amount of animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N year^{-1})
F_{CR}	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 year^{-1})
F_{SOM}	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 year^{-1})
EF_1	emission factor for N_2O emissions from N inputs (kg N_2O–N (kg N input)$^{-1}$)
EF_{1FR}	emission factor for N_2O emissions from N inputs to flooded rice (kg N_2O–N (kg N input)$^{-1}$)

$$\begin{aligned} N_2O{-}N_{OS} = {} & \left[\left(F_{OS,CG,Temp} \times EF_{2CG,Temp}\right) + \left(F_{OS,CG,Trop} \times EF_{2CG,Trop}\right) + \left(F_{OS,F,Temp,NR} \times EF_{2F,Temp,NR}\right)\right. \\ & \left. + \left(F_{OS,F,Temp,NP} \times EF_{2F,Temp,NP}\right) + \left(F_{OS,F,Trop} \times EF_{2F,Trop}\right)\right] \end{aligned} \tag{14}$$

where

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

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

where

F_{PRP}	annual amount of urine and dung N deposited by grazing animals on pasture, range, and paddock, kg N year^{-1}
$\mathrm{EF}_{3\mathrm{PRP}}$	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/pigs and sheep/other animals, respectively.

$$F_{\mathrm{ON}} = F_{\mathrm{AM}} + F_{\mathrm{SEW}} + F_{\mathrm{COMP}} + F_{\mathrm{OOA}} \tag{16}$$

$$F_{\mathrm{AM}} = N_{\mathrm{MMSAvb}} \times [1 - (\mathrm{Frac}_{\mathrm{FEED}} + \mathrm{Frac}_{\mathrm{FUEL}} + \mathrm{Frac}_{\mathrm{CNST}})] \tag{17}$$

$$F_{\mathrm{PRP}} = \sum_{T} \left[N_{(T)} \times N_{\mathrm{ex}(T)} \times \mathrm{MS}_{(T,\mathrm{PRP})} \right] \tag{18}$$

where

F_{ON}	total annual organic N fertilizer applied to soils other than by grazing animals (kg N year^{-1})
F_{AM}	annual amount of animal manure N applied to soils (kg N year^{-1})
F_{SEW}	annual amount of total sewage N that is applied to soils (kg N year^{-1})
F_{COMP}	annual amount of total compost N applied to soils (kg N year^{-1})
$N_{\mathrm{MMS\ Avb}}$	amount of managed manure N available for soil application, feed, fuel, or construction (kg N year^{-1})
$\mathrm{Frac}_{\mathrm{FEED}}$	fraction of managed manure used for feed
$\mathrm{Frac}_{\mathrm{FUEL}}$	fraction of managed manure used for fuel
$\mathrm{Frac}_{\mathrm{CNST}}$	fraction of managed manure used for construction
$N_{(T)}$	number of head of livestock species/category T in the country
$N_{\mathrm{ex}(T)}$	annual average N excretion per head of species/category T (kg N animal^{-1} year^{-1})
$\mathrm{MS}_{(T,\ \mathrm{PRP})}$	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 12–18 % organic carbon. Indian soils are generally deficient of organic carbon (<1 %). Only some soils in Kerala and the northeast hill regions contain higher organic carbon (5 %). Therefore, the area under organic soil has been taken as nil (Bhatia et al. 2004).

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, and 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 were estimated by Eq. 19.

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

where,

$N2O_{(ATD)}$–N	annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils (kg N_2O–N $year^{-1}$)
F_{SN}	annual amount of synthetic fertilizer N applied to soils (kg N $year^{-1}$)
Frac $_{GASF}$	fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx (kg N volatilized (kg of N applied)$^{-1}$)
F_{ON}	annual amount of managed animal manure, compost, sewage sludge, and other organic N additions applied to soils (kg N $year^{-1}$)
F_{PRP}	annual amount of urine and dung N deposited by grazing animals on pasture, range, and paddock (kg N $year^{-1}$)
Frac $_{GASM}$	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 NOx (kg N volatilized [kg of N applied or deposited]$^{-1}$)
EF_4	emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N–N_2O [kg NH_3–N + NOx–N volatilized]$^{-1}$)

N_2O emissions from leaching and runoff in regions where leaching and runoff occurs were estimated using Eq. 20:

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

where

$N_2O_{(L)}$–N	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 $year^{-1}$)
F_{SN}	annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs (kg N $year^{-1}$)
F_{ON}	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 $year^{-1}$)
F_{PRP}	annual amount of urine and dung N deposited by grazing animals in regions where leaching/runoff occurs (kg N $year^{-1}$)
F_{CR}	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 $year^{-1}$)

F_{SOM}	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 year^{-1})
$\mathrm{Frac}_{\ \mathrm{LEACH\text{-}}(H)}$	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 $[\text{kg of N additions}]^{-1}$)
EF_5	emission factor for N_2O emissions from N leaching and runoff (kg N_2O–N $[\text{kg N leached and runoff}]^{-1}$)

Conversion of $N_2O_{(\mathrm{ATD})}$–N and $N_2O_{(\mathrm{L})}$–N emissions to N_2O emissions was calculated using Eq. 21:

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

Large quantities of agricultural waste are produced from the farming systems in the form of crop residue. The 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 (IPCC 1997). However, it is a significant net source of CH_4, CO, NOx, and N_2O. In this study, the emissions are calculated for two GHGs—CH_4 and N_2O. Non–CO_2 emissions from crop residue burning were calculated using Eq. 22:

$$\mathrm{EBCR} = \sum \text{crops}\ (A \times B \times C \times D \times E \times F) \tag{22}$$

where

EBCR	Emissions from residue burning
A	Crop production
B	Residue-to-crop ratio
C	Dry matter fraction
D	Fraction burnt
E	Fraction actually oxidized
F	Emission factor

GHG Emissions from the Livestock Sector. Major activities resulting in the emission of greenhouse gases from animal husbandry are enteric fermentation and 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 such as the type of digestive tract, age and weight of the animal, and 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 nonruminant livestock (pigs, horses). CH_4 emissions from enteric fermentation were calculated using Eq. 23:

$$\text{Emissions} = \text{EF}_{(T)} \times N_{(T)} \times 10^{-6} \tag{23}$$

where

Emissions	methane emissions from enteric fermentation (Gg CH_4 year^{-1})
$\text{EF}_{(T)}$	emission factor for the defined livestock population (kg CH_4 head^{-1} year^{-1})
$N_{(T)}$	the number of heads of livestock species/category T
T	species/category of livestock

To estimate the total emissions from enteric fermentation, the emissions from different categories and subcategories were summed together.

Methane emissions from manure management were calculated using Eq. 24:

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

where

Emissions	methane emissions from manure management (Gg CH_4 year^{-1})
$\text{EF}_{(T)}$	emission factor for the defined livestock population (kg CH_4 head^{-1} year^{-1})
$N_{(T)}$	the number of head of livestock species/category T
T	species/category of livestock

Nitrous oxide emissions from manure management were calculated by Eq. 25:

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

where

Emissions	nitrous oxide emissions from manure management (Gg CH_4 year^{-1})
$\text{EF}_{(T)}$	emission factor for the defined livestock population (kg N head^{-1} year^{-1})
$N_{(T)}$	the number of heads of livestock species/category T
T	species/category of livestock
N–excretion	nitrogen excretion value for the livestock (kg head^{-1} year^{-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, nondairy cattle, young cattle, and buffaloes were taken as 60, 40, 25, and 46.5 kg/head/yr, respectively.

Table 8 Methane emission factors (EFs) used to calculate emissions from livestock management

Livestock	EF for enteric fermentation (kg CH_4/head/year)[a]	EF for manure management (kg CH_4/head/year)[a]
Dairy cattle	46	3.6
Nondairy 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

Source [a] Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 1997), Gurjar et al. (2004)

GHG Emissions from the 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 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 (IPCC 2001a, b). The IPCC method for estimating CH_4 emissions from SWDS is based on the first-order decay 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 method 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; then, the bacteria responsible for decay consume the degradable carbon in the waste, causing emissions to decrease (IPCC 2006). CH_4 emissions from SWDS were calculated by Eq. 26:

$$\text{Emissions CH}_4 = \left[\left[\text{MSW} \times \text{MCF} \times \text{DOC} \times \text{DOC}_f \times F \times 16/12\right] - R\right] \times (1 - \text{OF}) \tag{26}$$

where

MSW	mass of waste deposited (Gg/year)
MCF	methane correction factor for aerobic decomposition in the year of deposition (fraction)
DOC	degradable organic carbon in the year of deposition (Gg C/Gg waste)
DOC $_f$	fraction of degradable organic carbon that decomposes (fraction)
F	fraction of CH_4 in generated landfill gas (fraction)
R	methane recovery (Gg/year)
16/12	molecular weight ratio CH_4/C (ratio)
OF	oxidation factor (fraction)

The 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. An MCF of 0.4 was used in this study for unmanaged and shallow landfills (IPCC 2006). A degradable organic carbon value of 0.11 was obtained from NEERI (2005). The fraction of degradable organic carbon that decomposes (DOC_f) was taken as 0.5 (IPCC 2006) the fraction of CH_4 (F) in generated landfill gas was taken as 0.5 (IPCC 2006). It was considered that the there is no CH_4 recovery in the disposal sites in the major cities, and the oxidation factor was taken as zero for unmanaged and uncategorized solid waste disposal systems.

When treated or disposed anaerobically, wastewater can be a source of CH_4 and also N_2O emissions. Domestic, commercial, and industrial sectors are the sources of wastewater. The wastewater generated may be treated onsite or in a centralized plant, or disposed untreated to nearby bodies of water. Wastewater in closed underground sewers is not believed to be a significant source of CH_4. The wastewater 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 (Nicholas 2006). 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 a few cases industrial wastewater is discharged directly into the water bodies (IPCC 2006).

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. An increase 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, and washing machines (IPCC 2006). Equation 27 was used to estimate CH_4 emissions from domestic wastewater:

$$\mathrm{CH_4 emissions} = \left[\sum_{i,j}(U_i \times T_{i,j} \times \mathrm{EF}_j)\right](\mathrm{TOW} - S) - R \qquad (27)$$

where

CH_4 Emissions	CH_4 emissions in inventory year (kg CH_4/year)
TOW	total organics in wastewater in inventory year (kg BOD/year)
S	organic component removed as sludge in inventory year (kg BOD/year)

U_i	fraction of population in income group i in inventory year
$T_{i,j}$	degree of utilization of treatment/discharge pathway or system, j, for each income group fraction i in inventory year
i	income group: rural, urban high income, and urban low income
j	each treatment/discharge pathway or system
EF_j	emission factor (kg CH_4/kg BOD)
R	amount of CH_4 recovered in inventory year (kg CH_4/year)

The emission factor (EF_j) was calculated using Eq. 28:

$$\mathrm{EF}_j = \mathrm{Bo} \times \mathrm{MCF}_j \tag{28}$$

where

EF_j	emission factor (kg CH_4/kg BOD)
j	each treatment/discharge pathway or system
Bo	maximum CH_4 producing capacity (kg CH_4/kg BOD)
MCF_j	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), as given by Eq. 29:

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

where

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

N_2O emissions can occur as both direct and indirect emissions. Direct emissions are from the treatment plants, whereas indirect emissions are 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 (IPCC 2006). Equation 30 was used to estimate N_2O emissions from wastewater effluent:

$$N_2O\ \text{emissions} = N_{\text{effluent}} \times \mathrm{EF}_{\text{effluent}} \times 44/28 \tag{30}$$

where

N_2O emissions	N_2O emissions in inventory year (kg N_2O/year)
N_{effluent}	nitrogen in the effluent discharged to aquatic environments (kg N/year)
EF_{effluent}	emission factor for N_2O emissions from discharged to wastewater (kg N_2O–N/kg N)
44/28	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 2006).

Total nitrogen in the effluent was calculated by Eq. 31:

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

where

N effluent	total annual amount of nitrogen in the wastewater effluent (kg N/year)
P	human population
Protein	annual per capita protein consumption (kg/person/year)
F_{NPR}	fraction of nitrogen in protein (kg N/kg protein)
$F_{\text{NON–CON}}$	factor for nonconsumed protein added to the wastewater
$F_{\text{IND–COM}}$	factor for industrial and commercial co-discharged protein into the sewer system
N sludge	nitrogen removed with sludge (kg N/year)

Per capita protein consumption (Pr) value is taken as 21.462 (Nutritional Intake in India 2009–2010). The fraction of nitrogen in protein (F_{NPR}), fraction of non-consumption protein ($F_{\text{NON–CON}}$), and fraction of industrial and commercial co-discharged protein ($F_{\text{IND–COM}}$) values were taken as 0.16, 1.4 (fraction), and 1.25 (fraction) kg N/kg protein, respectively (IPCC 2006).

Industrial wastewater may be treated onsite by the industries or can be discharged into domestic sewer systems. The emissions are included in domestic wastewater emissions if released into the sewer system. Methane is produced only from industrial wastewater with significant carbon loading that is treated under intended or unintended anaerobic conditions (IPCC 2006). Major industrial wastewater sources having high CH_4 production potential are pulp and paper manufacture, meat and poultry industry, alcohol, beer and starch production, organic chemical production, and food and drink processing industries. In this study, industrial wastewater emissions were calculated based on the data availability from the industries located within the city limits. The method for estimation of CH_4 emissions from onsite industrial wastewater treatment is given in Eq. 32:

$$\mathrm{CH_4\ emissions} = \sum_i (\mathrm{TOW}_i - S_i)\ \mathrm{EF}_i - R_i \tag{32}$$

where

CH_4 Emissions	CH_4 emissions in inventory year (kg CH_4/year)
TOW_i	total organically degradable material in wastewater from industry *i* in inventory year (kg COD/year)
i	industrial sector
S_i	organic component removed as sludge in inventory year (kg COD/year)
EF_i	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 a weighted average is taken for this factor:

R_i amount of CH_4 recovered in inventory year, kg CH_4/year

The emission factor (EF_j) for each treatment/discharge pathway or system was calculated using Eq. 33:

$$\mathrm{EF}_j = \mathrm{Bo} \times \mathrm{MCF}_j \tag{33}$$

where

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

The TOW is a function of industrial output (product) *P* (tons/year), wastewater generation W (m^3/ton of product), and degradable organics concentration in the wastewater COD (kg COD/m^3):

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

where

TOW	total organically degradable material in wastewater for industry '*i*' (kg COD/year)
i	industrial sector
P_i	total industrial product for industrial sector i (t/year)
W_i	wastewater generated (m^3/t_{product})
COD_i	chemical oxygen demand (kg COD/m^3)

3 Results and Discussion

3.1 GHG Emissions from the 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 domestic and industrial sections are represented independently under their respective sectors.

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 the domestic and industrial sectors are attributed to the respective sector, along with the emissions from fuel consumption and industrial processes. GHG emissions from electricity consumption in the commercial sector and other sectors are represented in isolation for comparative analysis among the cities. Emissions resulting from auxiliary power consumption in plants located within the city boundaries and from the supply loss were also calculated in this study.

Figure 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 2009–10, the 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 subcategories (which includes Delhi International Airport Limited, Delhi Jal Board, Delhi Metro Rail Corporation, 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 cities in Table 9.

Fugitive Emissions. The intentional or unintentional release of greenhouse gases that occurs during the extraction, production, processing or transportation of fossil fuels is known as fugitive emissions (IPCC 2006). In the present study, fugitive emissions occurring from refinery crude throughput activity were estimated for Greater Mumbai city. The CH_4 emissions were found to be 0.0013 Gg for the year 2009–10, which gives a converted value of 0.033 Gg of CO_2 equivalents.

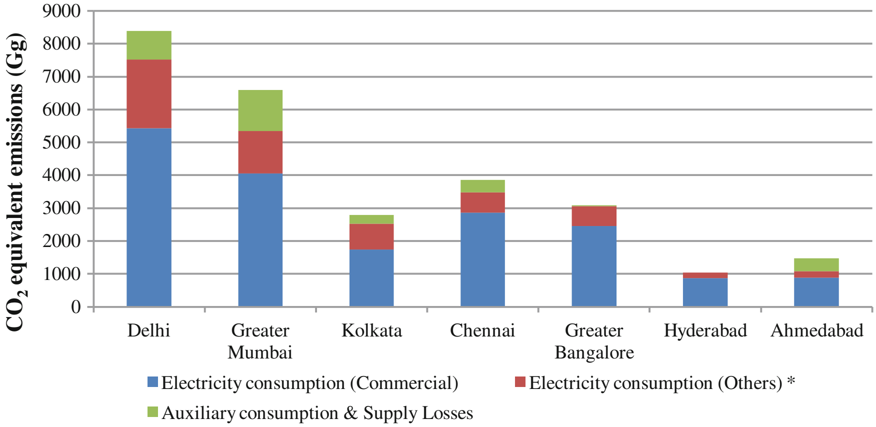

Fig. 3 Carbon dioxide equivalent emissions (CO_2 eq) from electricity consumption

Table 9 CO_2 equivalent emissions from electricity consumption by city

Cities	Commercial sector		Others[a]		Auxiliary consumption and supply losses	
	Gg	%	Gg	%	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

Note [a] Others include electricity consumption in street lights, advertisements, public water works and sewer systems, irrigation and agriculture, pumping systems, religious/worship, and crematoriums and burial grounds

3.2 GHG Emissions from the Domestic Sector

The domestic sector contributes a considerable amount of emissions in city-level studies. The major sources include electricity consumption for lighting and other household appliances and consumption of fuel for cooking. In the present study, GHGs emitting from electricity consumption in domestic sector and fuel consumption were calculated. The major fuels used in this study are LPG, piped natural gas (PNG), and kerosene, based on the availability of data.

Figure 4 shows the total GHG emissions converted in terms of CO_2 equivalent from the domestic sector in major cities. In Delhi during the base year 2009, 11690.43 Gg of CO_2 equivalents were emitted from the domestic sector, which is the highest among all the cities, accounting for 26.4 % of the total emissions when compared with the other six cities (Fig. 4). Electricity consumption accounted for

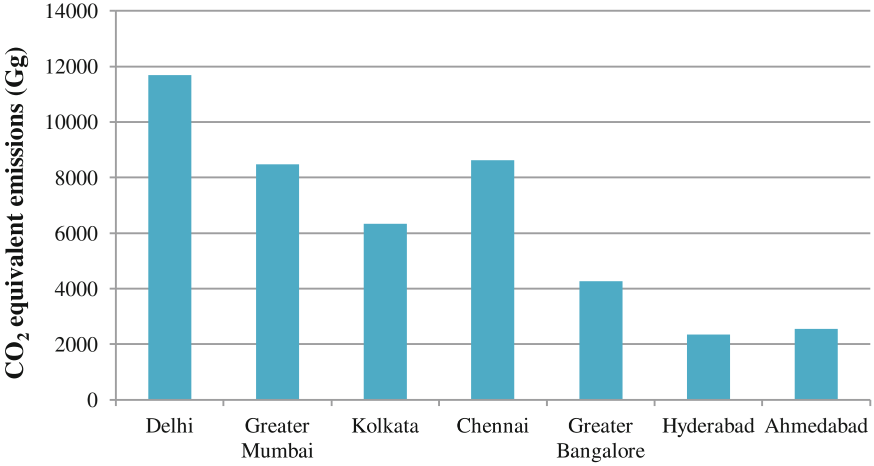

Fig. 4 Carbon dioxide equivalent emissions (CO_2 eq) from the domestic sector

9237.73 Gg of emissions out of the total domestic emissions. Earlier estimate show an emission of 5.35 million tons (5350 Gg) of CO_2 emissions from the domestic sector in Delhi during the year 2007–08 (Dhamija 2010). Greater Mumbai, which covers both Mumbai city and the suburban district, emits 8474.32 Gg of CO_2 equivalents from the domestic sector, which shares 19.14 % of the total emissions. The domestic sector in Kolkata results in 6337.11 Gg of CO_2 equivalents (14.31 % of total emissions).

Chennai ranks second in the list with 8617.29 Gg of CO_2 equivalents, contributing to approximately 19.5 % of total emissions. Greater Bangalore accounts for 4273.81 Gg of emissions from the domestic sector, which is 9.65 % of total emissions from the domestic sector. Hyderabad and Ahmedabad are responsible for 2341.81 Gg of CO_2 equivalent and 2544.03 Gg of CO_2 equivalent, respectively. These two cities together share 11 % of the total domestic emissions.

3.3 GHG Emissions from the Transportation Sector

In the major cities, the transportation sector is one of the major anthropogenic contributors of greenhouse gases (Mittal and Sharma 2003). Emissions resulting from the vehicles registered within the city boundaries and also from CNG-fuelled vehicles (if present) were calculated. Navigational activities from the port cities are also included in the emissions inventory on the basis of fuel consumption. Delhi has the highest emissions of the cities because it has the largest number of vehicles. According to the Transport Department in Delhi, the total number of vehicles in Delhi is more than the combined total vehicles in Mumbai, Chennai, and Kolkata. Delhi has 85 private cars per 1,000 population versus the

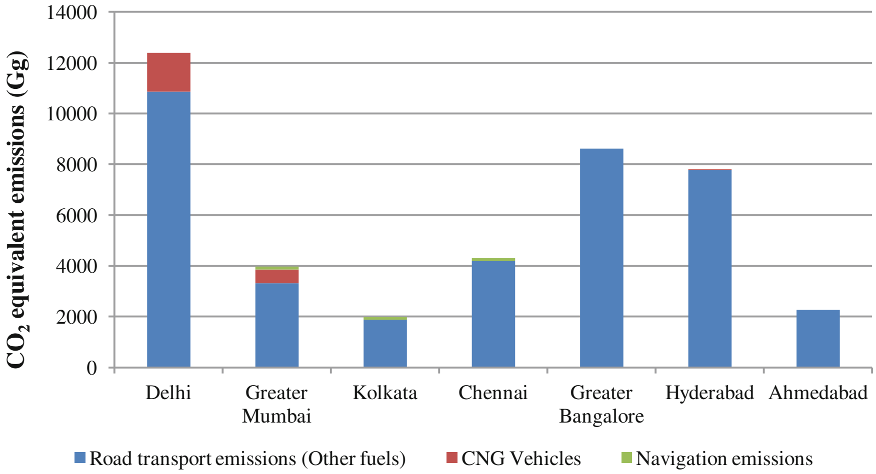

Fig. 5 Carbon dioxide equivalent emissions (CO_2 eq) from the transportation sector

country-wide average of 8 private cars per 1,000 population (SOE 2010). Delhi also had 344,868 CNG vehicles during the year 2009–10 (MoPNG 2010). Emissions resulting from road transportation, including CNG vehicles, and also in the port cities of India are depicted in Fig. 5.

In Delhi during the year 2009–10, total number of registered vehicles was 6,451,883, out of which there were approximately 20 lakhs of cars and jeeps and 40.5 lakhs of motorcycles, including scooters and mopeds. CNG-fuelled vehicles emitted 1527.03 Gg of CO_2 equivalents, whereas the remaining vehicles resulted in 10867.51 Gg of emissions, contributing almost 30 % of the total emissions in this subcategory, which is the highest among all the major cities. This is twice the earlier estimate of 5.35 million tons (5,350 Gg) of CO_2 emissions from road transportation sector in Delhi during the year 2007–08, or emissions of 7,660 Gg using the top–down approach and 8,170 Gg using the bottom-up approach (Dhamija 2010). CNG vehicles are also present in two other cities: Greater Mumbai and Hyderabad. Emissions from CNG vehicles in Mumbai during the year 2009–10 were found to be 531.34 Gg of CO_2 equivalents; for Hyderabad, it was estimated that 21.55 Gg of CO_2 equivalent was emitted from CNG vehicles during the study year. The emission inventories for the transportation sector in all the major cities are given in Table 10.

3.4 GHG Emissions from the Industrial Sector

Emissions were estimated from the major industrial processes that emit considerable GHGs and are located within the city boundaries (Table 11). Electricity consumption in the industrial sector was taken into account, from which the resulting emissions were calculated. Fuel consumption data were also used in a

Table 10 CO_2 equivalent emissions from the transportation sector in different cities

Cities	Road transportation emissions (Gg)		Navigation emissions (Gg)
	Vehicles using fuel other than CNG	CNG vehicles	
Delhi	10867.51	1527.03	_
Greater Mumbai	3320.66	531.34	114.18
Kolkata	1886.60	_	83.06
Chennai	4180.28	_	127.37
Greater Bangalore	8608.00	_	_
Hyderabad	7788.02	21.55	_
Ahmedabad	2273.72	_	_

Table 11 CO_2 equivalent emissions from the industrial sector by city

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

few of the industries to estimate the emissions. The iron and steel industry, cement industry, fertilizer plants, and chemical manufacturing are some major industries that release huge amounts of GHGs into the atmosphere during the process. Emissions were calculated from the major polluting industries in city boundaries because the data were not available for small- and medium-scale industries.

Emissions were calculated for ammonia production from the fertilizer industries in Greater Mumbai and Chennai. In Greater Mumbai during the year 2009–10, 654.5 Gg of CO_2 equivalents were emitted from the fertilizer industry. Emissions from the fertilizer industry in Chennai were found to be 223.28 Gg of CO_2 equivalents from the production of ammonia. Emissions were also calculated for the glass industry (Greater Mumbai, Greater Bangalore), paper industry (Kolkata), and petroleum products (Chennai) using the fuel consumption data. Although this study does not present the entire emissions across industrial sectors in a city due to unavailability of data, the major GHG-emitting industries were included, along with the electricity consumption, which constitutes most of the emissions. Figure 6 shows the emissions across different cities.

3.5 GHG Emissions from Agricultural Activities

CH_4 emissions from paddy cultivation and N_2O emissions from soil management are the major sectors responsible for GHG emissions from this sector. Crop residue

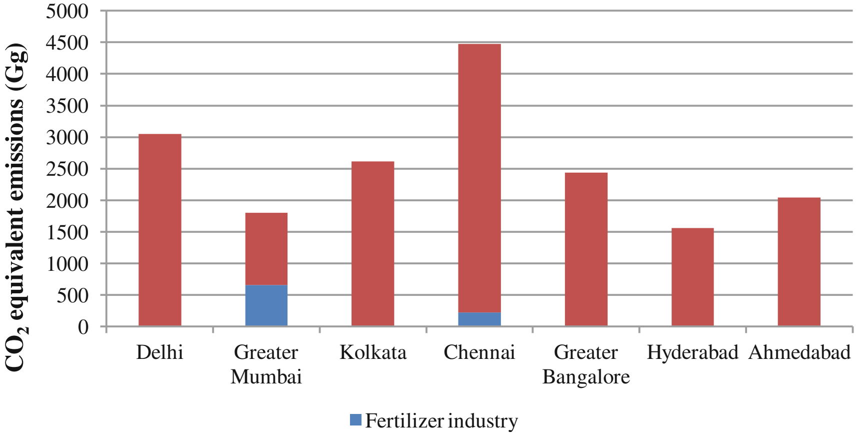

Fig. 6 Carbon dioxide equivalent emissions (CO_2 eq) from the industrial sector

Table 12 CO_2 equivalent emissions from agricultural 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	_

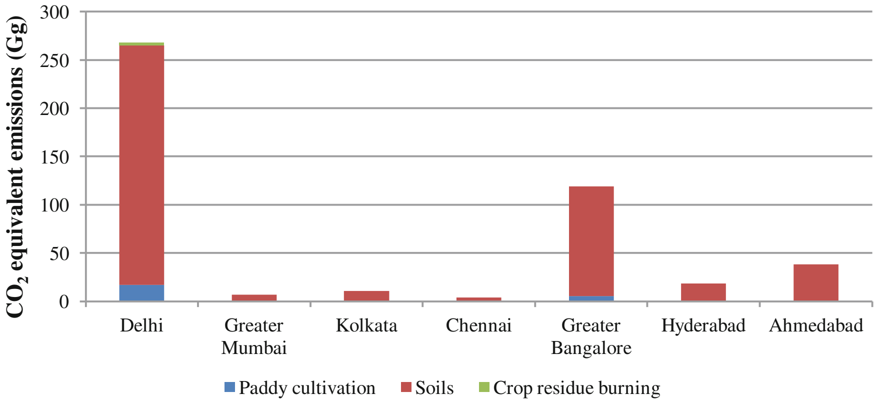

Fig. 7 Carbon dioxide equivalent emissions (CO_2 eq) from agricultural activities

burning is practiced in a few of the northern parts of 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. Figure 7 shows 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 were found to be 17.05 Gg in Delhi and 5.10 Gg in Greater Bangalore, respectively. Emissions resulting from the burning of crop residues at the end of the growing year were estimated based on Delhi's emission of 2.68 Gg of CO_2 equivalents. N_2O emissions were 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.

3.6 GHG Emissions from Livestock Management

Enteric fermentation and manure management are the two major activities resulting in the emission of GHGs from animal husbandry. In the present study, emissions from livestock management were carried out to calculate the emissions resulting from enteric fermentation and manure management in the major cities. The livestock population for cities was obtained using the 2003 and 2007 livestock census, from which the number of livestock was extrapolated to the inventory year 2009 (MOA 2003, 2005, 2007, 2008). The emission estimates for the major cities are given in Table 13.

Delhi and Greater Bangalore emitted the highest amounts of greenhouse gases due to animal husbandry. The emissions resulting from enteric fermentation for Delhi and Greater Bangalore were estimated to be 570.57 Gg of CO_2 equivalent and 129.36 Gg of CO_2 equivalents, respectively. Similarly, Delhi and Greater Bangalore emitted 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. Figure 8 shows the emission profile of livestock management for different cities.

3.7 GHG Emissions from the Waste Sector

In the current study, GHG emissions from three major waste sectors were calculated: municipal solid waste, domestic wastewater, and industrial wastewater. CH_4 emissions from municipal solid waste disposal data were obtained from the local city municipality. CH_4 and N_2O emissions were calculated from the domestic

Table 13 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

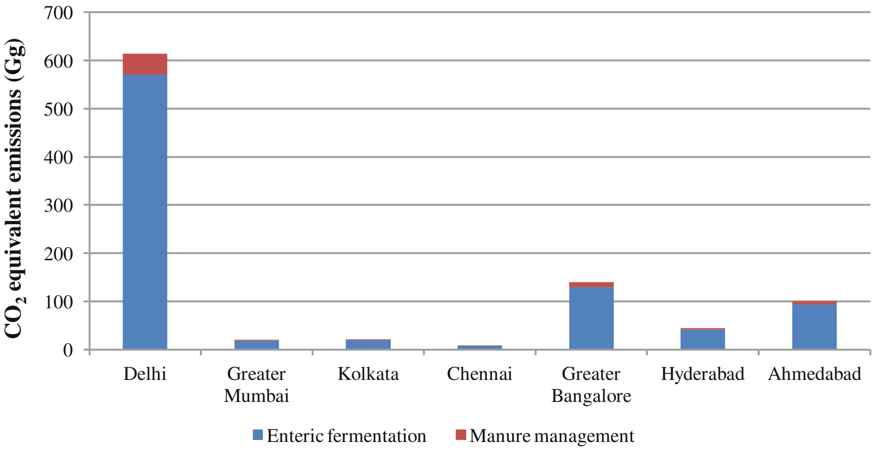

Fig. 8 Carbon dioxide equivalent emissions (CO_2 eq) from livestock management

Table 14 CO_2 equivalent emissions from the waste sector in different cities

Cities	Solid waste disposal		Domestic wastewater		Industrial wastewater (Gg)
	Gg	%	Gg	%	
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	_

sector. In this study, the industrial wastewater emissions were 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.

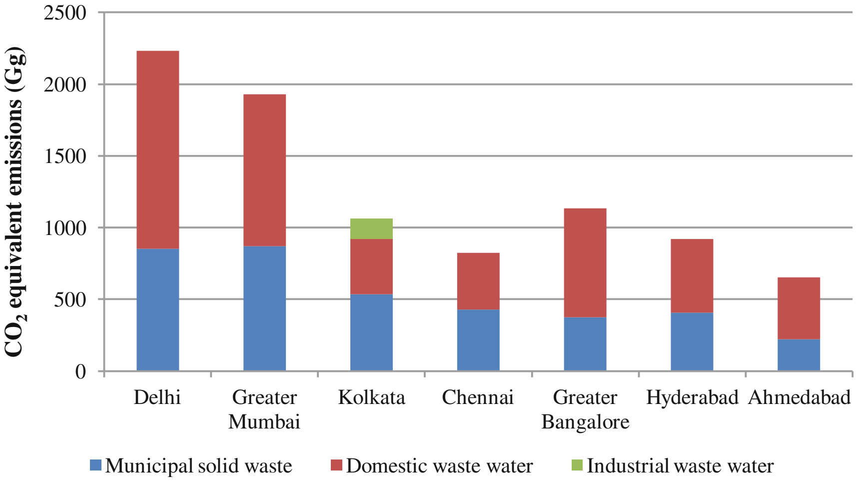

Fig. 9 Carbon dioxide equivalent emissions (CO_2 eq) from the waste sector

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 the IPCC (2006) method; together, these cities are responsible for almost 46.7 % of the total emissions occurring from solid waste disposal. The emissions depend on the parameters such as the amount of waste disposed, methane correction factor, degradable organic carbon, and oxidation factor IPCC (2006). Waste disposal in cities is a major source of anthropogenic CH_4 emissions 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, the major emitters from the domestic wastewater sector are Delhi, Greater Mumbai, and Greater Bangalore, which emit 1378.75, 1058.09, and 759.29 Gg of CO_2 equivalents, respectively. Emissions from the industrial wastewater 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.

3.8 Intercity Variations of Carbon Footprint

Economic activity is a key factor that affects GHG emissions. An increase in the economy results in an increase in demand for energy and energy-intensive goods, which will also increase emissions. On the other hand, the growth of a country's economy results in improvements in technologies and promotes the advancement of organizations that focus on environmental protection and mitigation of emissions. In this study, total carbon dioxide equivalent emissions emitted from major Indian cities were compared with their economic activity, measured in terms of GDP. CO_2 equivalent emissions from Delhi, Greater Mumbai, Kolkata, Chennai,

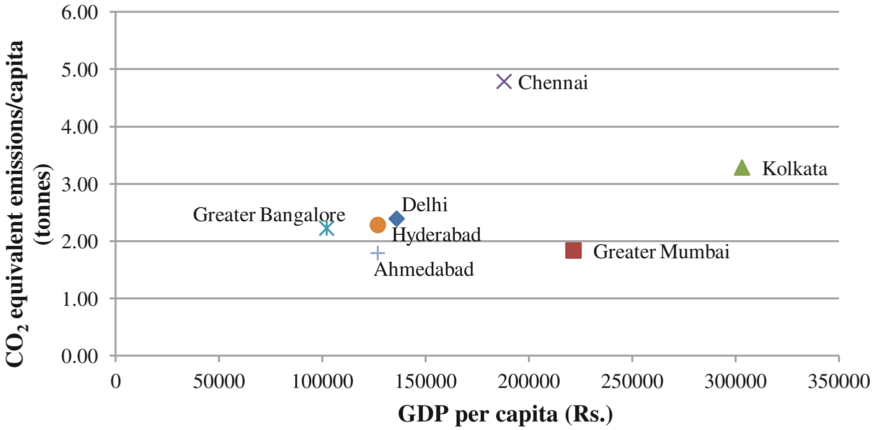

Fig. 10 CO_2 equivalent emissions per capita versus GDP per capita for all cities

Table 15 Values of CO_2 equivalent emissions/capita, GDP/capita and CO_2 equivalent emissions/GDP by city

Cities	CO_2 eq. emissions per capita (tonnes)	GDP per capita (Rs.)	CO_2 eq. emissions per GDP (tonnes CO_2/Lakh Rs.)
Delhi	2.40	136014.76	1.76
Greater Mumbai	1.84	221608.20	0.83
Kolkata	3.29	303187.96	1.08
Chennai	4.79	188020.64	2.55
Greater Bangalore	2.23	102161.49	2.18
Hyderabad	2.29	126936.59	1.80
Ahmedabad	1.80	126870.55	1.42

Greater Bangalore, Hyderabad, and Ahmedabad were found to be 38633.2, 22783.08, 14812.10, 22090.55, 19796.5, 13734.59, and 9124.45 Gg respectively. Figure 10 shows the relationship between carbon dioxide equivalent emissions per capita to GDP per capita.

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

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

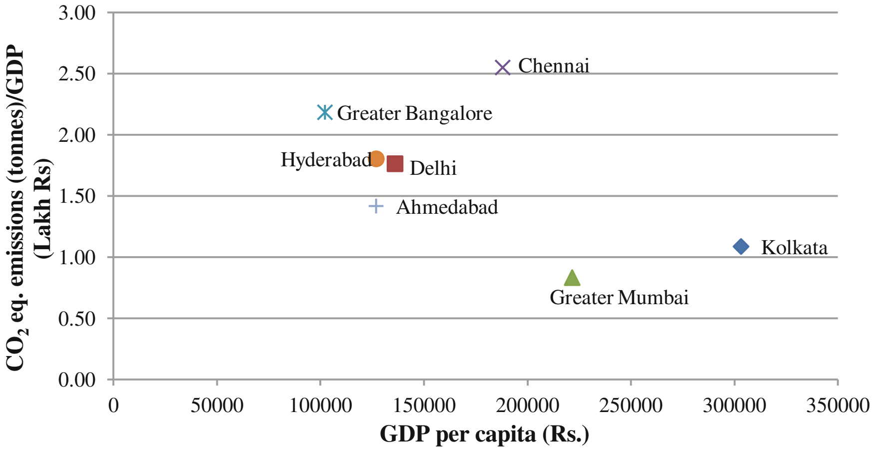

Fig. 11 CO_2 equivalent emissions per GDP versus GDP per capita for all cities

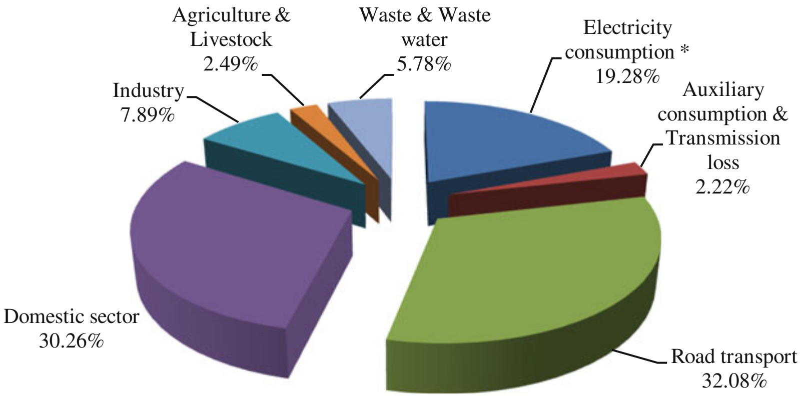

Fig. 12 Carbon dioxide equivalent emissions (Gg) in Delhi

3.9 Carbon Footprint: City and Sector

The aggregation of the carbon footprint of all sectors revealed that carbon emissions in major cities in India ranges from 38633.20 Gg/year (Delhi), 22783.08 (Greater Mumbai), 22090.55 (Chennai), 19796.60 (Greater Bangalore), 14812.10 (Kolkata), to 13734.59 (Hyderabad). Annex 1 details the sector-wise carbon footprint of the major cities in India.

Sector-wise carbon footprint analysis for Delhi (Fig. 12) revealed that the transport sector leads the carbon emissions (32.08 %), followed by the domestic sector (30.26 %) and electricity consumption (19.28 %). Electricity consumption includes public lighting, general purpose, temporary, and colony lighting.

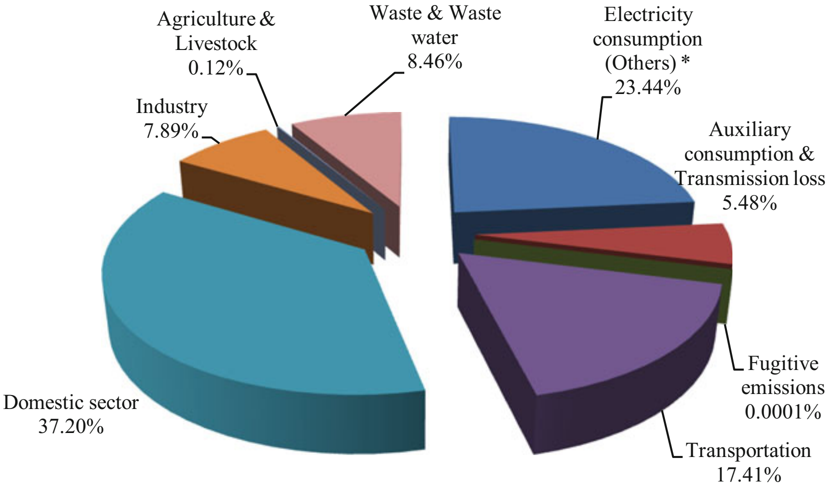

Fig. 13 Carbon dioxide equivalent emissions (Gg) in Greater Mumbai

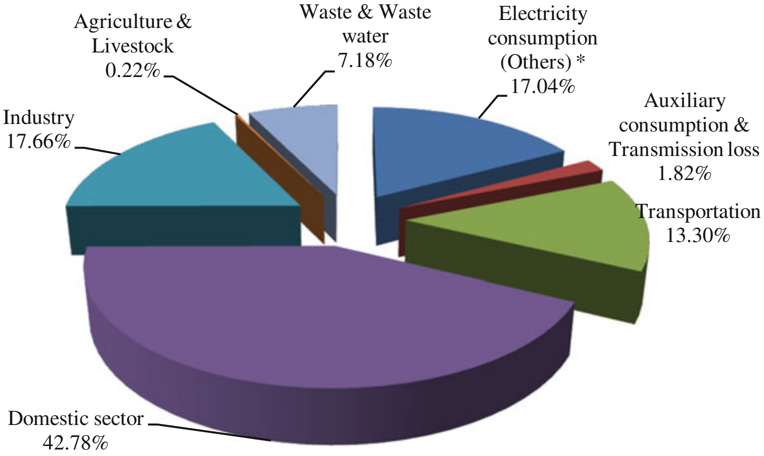

Fig. 14 Carbon dioxide equivalent emissions (Gg) in Kolkata

Figures 13, 14 and 15 depict the sector-wise carbon footprints for Mumbai, Kolkata, and Chennai. In these cities, the domestic sector has the highest carbon footprint, ranging from 42.78 % (Kolkata), 39.01 % (Chennai), to 37.2 % (Greater Mumbai). Next is the transport sector, at 19.50 % (Chennai), 17.41 % (Greater Mumbai), and 13.3 % (Kolkata).

Figures 16 and 17 illustrate the sector-wise carbon emissions for the information technology giants of India—Bangalore and Hyderabad. The lack of

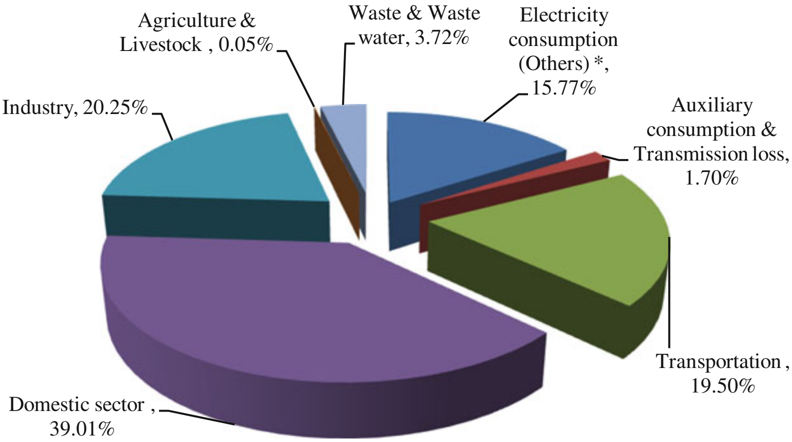

Fig. 15 Carbon dioxide equivalent emissions (Gg) from Chennai in 2009–10

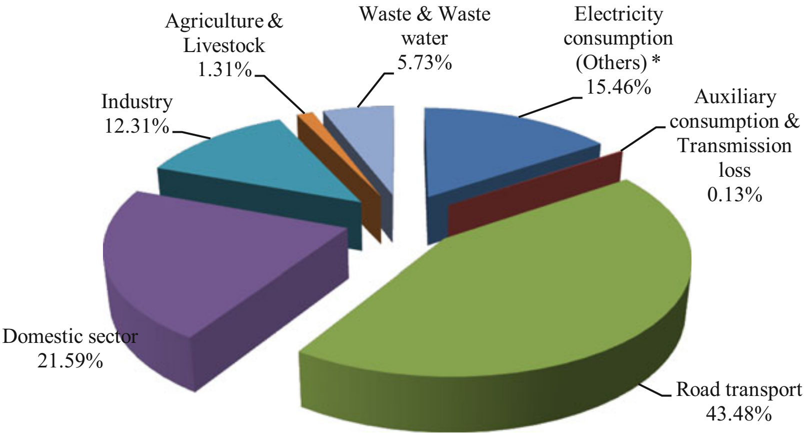

Fig. 16 Carbon dioxide equivalent emissions (Gg) in greater Bangalore

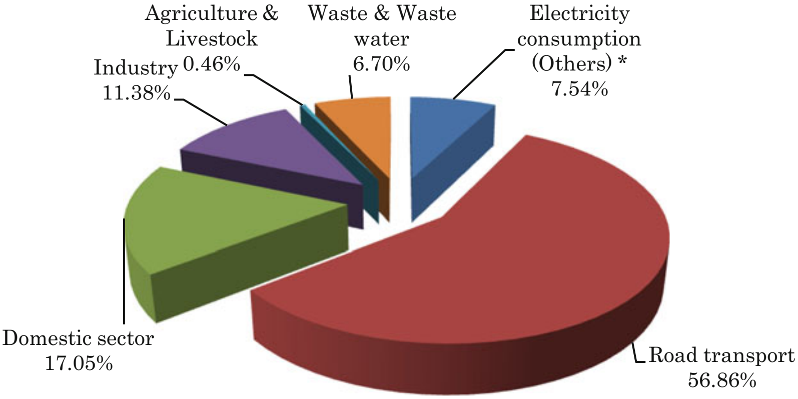

Fig. 17 Carbon dioxide equivalent emissions (Gg) in Hyderabad

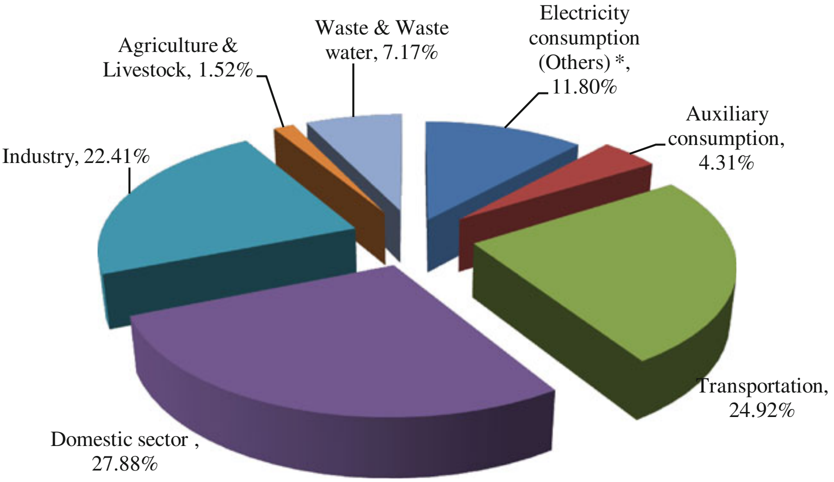

Fig. 18 Carbon dioxide equivalent emissions (Gg) in Ahmedabad

appropriate public transport systems in these cities and haphazard growth due to unplanned urbanization has led to large–scale use of private vehicles in these cities. Emissions from the transport sector range are 43.83 % in Greater Bangalore and 56.86 % in Hyderabad. Figure 18 depicts the carbon footprint of Ahmedabad city, with sector shares ranging from 27.88 % (domestic), 24.92 % (transportation), to 22.41 % (industry).

4 Conclusion

India is currently second most populous country in the world, and it contributes approximately 5.3 % of the total global GHG emissions. Major cities in India are witnessing rapid urbanization. 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 tons of CO_2 equivalent emissions per capita—the highest among all the cities—followed by Kolkata, which emits 3.29 tons of CO_2 equivalent emissions per capita. Chennai emits the highest CO_2 equivalent emissions per GDP (2.55 tons CO_2 eq/Lakh Rs.), followed by Greater Bangalore, which emits 2.18 tons CO_2 eq/Lakh Rs.

The carbon footprint of all the major cities in India helps to improve national-level emission inventories. In recent years, the popularity of the carbon footprint has grown, resulting in estimates of greenhouse gas emissions in the major metropolitan global cities and thereby framing regulations to reduce the emissions. The data regarding emissions from different sectors help the policy makers and city planners to devise mitigation strategies focusing on the particular sector, which helps to improve the environmental conditions within the city. Implementation of emission reduction strategies in cities also helps to gain carbon credits in the global markets, which has been an outcome of increased awareness about greenhouse gas emissions. Knowing the carbon footprint of major cities in India sector-wise would help planners in implementing appropriate mitigation measures.

- *Electricity consumption.* The calculation of greenhouse gas emissions from commercial and other sectors (public lighting, advertisements, railways, public water works and sewerage systems, irrigation, and agriculture) shows that energy consumption in the commercial sector is one of the major contributor of emissions in cities; it 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 had emissions of 7448.37 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 the commercial sector in cities is a major source of emissions.
- *Domestic sector.* The study reveals that the domestic sector causes the majority of the emissions in all the major cities due to the use of fossil fuels such as LPG, kerosene, and PNG for cooking purposes. Fossil fuels used for cooking purposes in households cause indoor air pollution. Consumption of electricity in the domestic sector for lighting, heating, and household appliances also share a major portion of emissions. It is calculated that the domestic sector resulted in emissions of 11690.43 Gg of CO_2 equivalents ($\sim$30 % of the total emissions) in Delhi, which is the highest among all the cities, followed by Chennai and Greater Mumbai, which emit 8617.29 Gg ($\sim$39 % of total emissions) and 8474.32 Gg of CO_2 equivalents ($\sim$39 % of total emissions), respectively. GHG emissions from the domestic sector in cities show the scope for cleaner fuels for cooking through the renewable sources, such as solar energy for water heating and other household purposes.
- *Transportation sector.* Road transport is another chief sector causing major emissions in cities. From the results obtained, the major emitters are Delhi and Greater Bangalore, which emit 12394.54 and 8608 Gg of CO_2 equivalents, respectively. The transportation sector is a major source of emissions when city-level studies are carried out. Emissions from CNG vehicles in a few of the cities were calculated, along with fuel consumption for navigation in the port cities. Lesser polluting fuels, such as LPG and CNG, can be made compulsory in major cities, phasing out older and inefficient vehicles; extensive public transport also helps to reduce pollution.
- *Industrial sector.* The industrial sector contributes approximately 10–20 % of the total emissions in all the major cities. In this study, electricity consumption in industries is calculated for all the cities, as well as emissions from major

industries located within the city boundaries. Chennai city was found to be the highest emitter, at 4472.35 Gg of CO_2 equivalents. There are insufficient data for medium- and small-scale industries located within the cities.

- *Agriculture and livestock activities*. Due to increasing urbanization, there are not many agricultural activities and animal husbandry practiced in the major metropolitan cities. This sector accounts for less than 3 % of total emissions among the cities. Delhi and Greater Bangalore emit 961 and 258.6 Gg of CO_2 equivalents due to livestock management and agricultural activities, respectively. The results prove that the agricultural practices are decreasing in cities due to increases in urban growth.
- *Waste sector*. Management and treatment of solid and liquid waste in cities results in emissions. This sector shares 3–9 % of total emissions from the cities. Delhi and Greater Mumbai emit the greatest amounts—2232 and 1928 Gg of CO_2 equivalents—compared with other cities. The waste sector therefore accounts for a considerable amount of greenhouse gas emissions when city-level studies are carried out.

5 Scope of Further Research

- Developing national-level emission factors for processes that have no country-specific emission factors helps to improve 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 wastewater treatment data for different years, help to improve the values obtained from these sectors for a particular inventory year.
- Based on the results obtained, policies should be framed to focus on the reduction of emissions from the targeted sector. For example, in cities with higher domestic emissions, the use of cleaner fuels (e.g., LPG, PNG) should be made mandatory, as should the utilization of solar energy for lighting and water heating. For cities with higher transportation emissions, less polluting fuels (e.g. LPG, CNG) may be made compulsory in vehicles such as cars, auto rickshaws, and buses, introducing more public transportation services and phasing out older vehicles. This helps the local authorities to draft regulations resulting in the mitigation of environmental degradation in cities.

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A.1 6 Annexure

Carbon footprint of Delhi

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Nondomestic	5402.6	0.079	0.081	5428.6
Railway traction and Delhi metro rail corporation	456.31	0.007	0.007	458.51
Others[a]	1553.8	0.023	0.023	1561.3
1(a) *Auxiliary consumption and supply losses*	853.55	0.011	0.013	857.69
2. *Road transportation*				
Vehicles using fuels other than CNG	10405	12.77	0.479	10868
CNG vehicles	1371.4	2.99	0.272	1527
3. *Domestic sector*	11639	0.353	0.144	11690
4. *Industrial sector*	3034.7	0.044	0.045	3049.3
5. *Agriculture*				
Paddy cultivation	_	0.682	_	17.05
Soils	_	_	0.833	248.26
Burning of crop residue	_	0.079	0.002	2.68
Electricity	78.92	0.001	0.001	79.3
6. *Livestock management*				
Enteric fermentation	_	22.82	_	570.57
Manure management	_	1.72	0.0002	43.09
7. *Waste*				
Municipal solid waste	_	34.13	_	853.19
Domestic waste water	_	46.07	0.761	1378.8
Total	**34795**	**121.79**	**2.66**	**38633**

Note [a] Others include electricity consumption in worship/hospital, staff, Delhi International Airport Limited, Delhi Jal Board

Carbon footprint of greater Mumbai

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	4031.80	0.071	0.055	4049.85
Others[a]	1285.73	0.023	0.017	1291.49
1(a) *Auxiliary consumption and supply losses*	1242.14	0.024	0.016	1247.54

(continued)

(continued)

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1(b) *Fugitive emissions*				
Refinery crude throughput	_	0.0013	_	0.033
2.a. *Road transportation*				
Vehicles using fuels other than CNG	3174.58	3.85	0.168	3320.66
CNG vehicles	471.18	1.12	0.108	531.34
2.b. *Navigation*	113.03	0.010	0.003	114.18
3. *Domestic sector*	8444.48	0.396	0.067	8474.32
4. *Industrial sector*				
Ammonia production	654.50	_	_	654.50
Glass industry	21.09	0.001	0.0002	21.16
Electricity consumption	1118.04	0.020	0.0151	1123.04
5. *Agriculture*				
Soils	_	_	0.023	6.95
6. *Livestock management*				
Enteric fermentation	_	0.746	_	18.66
Manure management	_	0.055	0.000006	1.38
7. *Waste*				
Municipal solid waste	_	34.80	_	869.92
Domestic waste water	_	35.36	0.584	1058.09
Total	**20556.56**	**76.47**	**1.06**	**22783.08**

Note [a] Others include electricity consumption in advertisements, railways, street light, religious, crematorium and burial grounds

Carbon footprint of Kolkata

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	1737.79	0.018	0.027	1746.34
Metro and tramways	104.01	0.001	0.002	104.52
Others[a]	669.64	0.007	0.010	672.93
1(a) *Auxiliary consumption and supply losses*	268.11	0.003	0.004	269.43
2. *Road transportation*	1773.78	1.41	0.260	1886.60
3. *Navigation*	82.22	0.008	0.002	83.06
3(a) *Domestic sector*	6312.22	0.239	0.064	6337.11
4. *Industrial sector*	2603.03	0.027	0.002	2615.84
5. *Agriculture*				
Soils	_	_	0.035	10.54

(continued)

(continued)

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
6. *Livestock management*				
Enteric fermentation	_	0.788	_	19.70
Manure management	_	0.073	0.000004	1.83
7. *Waste*				
Municipal solid waste	_	21.41	_	535.33
Domestic waste water	_	12.87	0.213	385.03
Industrial waste water	_	5.75	_	143.84
Total	**13550.80**	**42.61**	**0.619**	**14812.10**

Note [a] Others include electricity consumption in educational institutions, hospitals, municipality, public water works and sewerage systems, pumping stations, street lighting, public utilities, sports complex and construction power

Carbon footprint of Chennai

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	2845.19	0.033	0.044	2859.07
Others[a]	621.15	0.007	0.010	624.18
1(a) *Auxiliary consumption and Supply losses*	373.78	0.004	0.006	375.61
2. *Road transportation*	3965.11	6.32	0.192	4180.28
3. *Navigation*	126.09	0.012	0.003	127.37
3(a) *Domestic sector*	8584.11	0.343	0.083	8617.29
4. *Industrial sector*	4452.26	0.059	0.062	4472.35
5. *Agriculture*				
Soils	_	_	0.013	3.73
6. *Livestock management*				
Enteric fermentation	_	0.304	_	7.61
Manure management	_	0.022	0.000002	0.55
7. *Waste*				
Municipal solid waste	_	17.13	_	428.27
Domestic waste water	_	13.17	0.218	394.24
Total	**20967.69**	**37.41**	**0.629**	**22090.55**

Note [a] others include electricity consumption in public lighting and water supply, advertisements, religious, and railway traction

Carbon footprint of greater Bangalore

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	2444.92	0.029	0.037	2456.80
Others[a]	600.54	0.007	0.009	603.46
1(a) *Auxiliary consumption and Supply losses*	24.76	0.001	0.0002	24.85
2. *Road transportation*	8288.55	7.65	0.430	8608.00
3. *Domestic sector*	4256.22	0.170	0.045	4273.81
4. *Industrial sector*	2425.28	0.029	0.037	2437.03
5. *Agriculture*				
Paddy cultivation	_	0.204	_	5.10
Soils	_	_	0.382	113.86
6. *Livestock management*				
Enteric fermentation	_	5.17	_	129.36
Manure management	_	0.411	0.000047	10.30
7. *Waste*				
Municipal solid waste	_	14.99	_	374.73
Domestic waste water	_	25.37	0.419	759.29
Total	**18040.29**	**54.04**	**1.36**	**19796.60**

Note [a] Others include electricity consumption in irrigation and agriculture, street lighting, water works, and Railways

Carbon footprint of Hyderabad

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	866.23	0.013	0.013	870.40
Others[a]	164.95	0.002	0.002	165.74
2. *Road Transportation*				
Vehicles using fuels other than CNG	7488.51	6.60	0.452	7788.02
CNG vehicles	18.64	0.066	0.004	21.55
3. *Domestic sector*	2331.35	0.055	0.030	2341.81
4. *Industrial sector*	1555.82	0.024	0.023	1563.14
5. *Agriculture*				
Soils	_	_	0.062	18.48
6. *Livestock management*				
Enteric fermentation	_	1.68	_	41.98
Manure management	_	0.122	0.00001	3.05

(continued)

(continued)

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
7. *Waste*				
Municipal solid waste	_	16.27	_	406.85
Domestic waste water	_	17.16	0.284	513.56
Total	**12425.50**	**41.99**	**0.870**	**13734.59**

Note [a] Others include electricity consumption in public lighting, general purpose, temporary and colony lighting

Carbon footprint of Ahmedabad

Sector	CO_2 emissions (Gg) 2009–2010	CH_4 emissions (Gg) 2009–2010	N_2O emissions (Gg) 2009–2010	CO_2 equivalent (Gg) 2009–2010
1. *Electricity consumption*				
Commercial sector	884.52	0.015	0.013	888.73
Others[a]	187.20	0.003	0.003	188.09
1(a) *Auxiliary consumption*	390.93	0.004	0.006	392.85
2. *Road Transportation*	2151.93	3.46	0.118	2273.72
3. *Domestic sector*	2532.60	0.059	0.033	2544.03
4. *Industrial sector*	2034.67	0.034	0.030	2044.35
5. *Agriculture*				
Soils	_	_	0.128	38.03
6. *Livestock management*				
Enteric fermentation	_	3.75	_	93.77
Manure management	_	0.266	0.00003	6.66
7. *Waste*				
Municipal solid waste	_	8.80	_	219.89
Domestic waste water	_	14.51	0.240	434.34
Total	**8181.85**	**30.91**	**0.57**	**9124.45**

Note [a] Others include electricity consumption in water pumping, drainage pumping stations, lighting and temporary supply

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