Environmental Footprints and Eco-design
of Products and Processes

Subramanian Senthilkannan Muthu *Editor*

Carbon Footprint Case Studies

Municipal Solid Waste Management, Sustainable Road Transport and Carbon Sequestration

Springer

Environmental Footprints and Eco-design of Products and Processes

Series Editor

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This book is dedicated to:

The lotus feet of my beloved Lord Pazhaniandavar

My beloved late Father

My beloved Mother

My beloved Wife Karpagam and Daughters—Anu and Karthika

My beloved Brother—Raghavan

Everyone working in various industrial sectors to reduce the carbon footprint to make our planet earth SUSTAINABLE

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About the Editor

Dr. Subramanian Senthilkannan Muthu currently working for SgT Group and API as the Head of Sustainability and is based out of Hong Kong. He earned his Ph.D. from The Hong Kong Polytechnic University and is a renowned expert in the areas of Environmental Sustainability in Textiles & Clothing Supply Chain, Product Life Cycle Assessment (LCA) and Product Carbon Footprint Assessment (PCF) in various industrial sectors. He has 5 years of industrial experience in textile manufacturing, research and development, and textile testing and over a decade of experience in Life Cycle Assessment (LCA), carbon and ecological footprints assessment of various consumer products. He has published more than 100 research publications, written numerous book chapters, and authored/edited over 95 books in the areas of Carbon Footprint, Recycling, Environmental Assessment, and Environmental Sustainability.

Carbon Footprint: Concept, Methodology and Calculation

Flavio Scrucca, Grazia Barberio, Valentina Fantin, Pier Luigi Porta, and Marco Barbanera

Abstract Carbon footprint (CF) is nowadays one of the most widely used environmental indicators and calculations of CF have been recently in very high demand. Many approaches, methodologies and tools, from simplified online calculators to other more scientific and complex life-cycle based methods, have been developed and are available for estimations. CF evaluations are, in general, focused on products and organizations, but calculation approach have been developed also for specific themes/sectors, such as for instance cities, individuals, households, farms, etc. This chapter is aimed at giving an updated and comprehensive overview on the concept of CF, and also on methodologies, technical standards, protocols and tools for its calculation. Attention is focused on the two main and usual scopes of CF assessment, i.e. products and organizations, but also on other relevant specific study subjects, also discussing methodological differences and issues.

Keywords Carbon footprint · Methodology · Life cycle assessment · Product environmental footprint · Carbon footprint calculators · Environmental labelling · Greenhouse gas emissions · Global warming

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1 Introduction

It is nowadays recognized that greenhouse gas (GHG) emission represents a global environmental problem [19], and that the nonstop emission of GHG by human activities is responsible for an aggravation of the global warming trend, with consequent negative effects on natural systems and also on the economies [76, 32].

The aim to reduce GHG emissions has gained—and is increasingly gaining—worldwide consensus and the global climate policies and actions (such as, for instance, the Paris Agreement or, at the European level, the recent Green Deal and the other key legislation and policies) confirm the international community effort to deal with global warming in a systemic and trans-sectoral way. The perspective of carbon emission analysis has been gradually turned from the "macro" (global/national scale) to the "micro" level, i.e. to the accounting of GHG emissions related to individual, products or corporate activities, so to understand the problem in depth and to develop specific measures.

In such a context, the concept of Carbon Footprint (CF) has considerably evolved, becoming an important and widely used indicator of GHG emissions that has played—and is still playing—an important role in popularizing the issues of climate change and environmental impact of systems and products along the whole life cycle. Accordingly, the life cycle thinking approach, that allows relationships among industrial issues, sustainability, research and innovation, has become commonly accepted as strategic.

Several approaches, methodologies and tools—from simplified online calculators to other more scientific and complex life-cycle based methods—have been developed and are available for CF estimations, with a main focus on products and organizations, but also considering specific themes/sectors. CF research, therefore, actually covers a wide range of topics, such as countries, cities, organizations, enterprises, families, and individuals, but different methodological issues (e.g. critical issues in defining the CF model) still affect CF calculation. According to this, not surprisingly, the topic "CF calculation methods" is one of the currently popular topics in research [87].

Moreover, in parallel to the CF concept evolution, other footprint concepts have been developed, also as a consequence of "communication issues" related to CF. As a matter of fact, it emerged that to provide a complete information on the environmental performance of a system/product to the general public, not GHG emissions but other environmental impacts are the most significant. Consequently, the need for developing a harmonized environmental footprint methodology that can be unique, representative and that comprise a set of relevant environmental performance indicators has become more and more concrete in recent years.

This chapter is aimed at giving an updated and comprehensive overview on the concept of CF, methodologies, technical standards, protocols and tools for its calculation and also at providing an insight on CF-derived footprints, such as the Product Environmental Footprint proposed by the European Commission.

Section 2 provides general overview on the evolution and the conceptualization of CF, presenting the main differences between its calculation at the organization and product level and also the related reference documents. In Sect. 3 attention is focused on the methodologies developed to calculate CF of products, also presenting an overview of the Product Environmental Footprint methodology proposed by the European Commission. Section 4 discusses the main critical issues in defining the CF model, focusing on key aspect such as the functional unit and the temporal dimension of the assessment, and also on modeling approaches and relevant—and debated—GHG emission sources. Finally, in Sect. 5 an analysis of publicly available CF calculators focused on different themes, also through a review of relevant related literature, is presented, in order to provide an overall insight into the typology of the available tools and the characteristics of the currently used approaches.

2 A General Overview on Carbon Footprint

In the last years, the concept of carbon footprint (CF), has been used widely as an indicator of environmental sustainability. CF refers to the total amount of greenhouse gas (GHG) emissions directly or indirectly produced by an activity or accumulated during a product life cycle and can be used to evaluate the main environmental hotspots and the mitigation or improvement measures [55, 60].

The concept of CF originated as a subset of "ecological footprint", which refers to the amount of productive land and sea area, expressed in hectares, to sustain human population [60, 81]. In this context, CF can be expressed as the land area required to assimilate the CO_2 produced by humanity. However, due to the importance of the global warming problem in the world environmental policy and actions, the use of CF became independent from the ecological footprint [60, 17]. Carbon footprinting has been used in the last years but in a slightly different way, i.e. a life cycle impact category indicator, named global warming potential (GWP) [21]. The present form of CF is thus a hybrid concept, stemming from "ecological footprint" but representing an indicator for GWP [60].

In fact, while an ecological footprint represents a measure of the regenerative capacity of the environment (in terms of a corresponding area of productive land), the present concept of CF stands for a measure of a physical quantity of carbon (or equivalent gases) resulting from defined activities.

On the basis of this concept, CF can be defined as the CO_2 equivalent (CO_2eq) mass based on 100 years GWP [3, 8, 60, 85]. In other words, CF is quantified by indicators such as global GWP, which is the quantity of GHGs contributing to global warming and climate change, with a 100 years time horizon [56]. To obtain CF results expressed in kgCO_2eq, the actual mass of a gas has to be multiplied by its GWP factor, in order to be able to compare the GW effect of different GHGs [12, 22, 56].

CF allows companies to identify the most important GHG sources and to analyse reduction potential, thus increasing productive efficiency at the same time [60, 7, 41]. In this way, environmental improvements and costs reductions can be achieved. Due to the growing market interest for environmentally-friendly products, and the

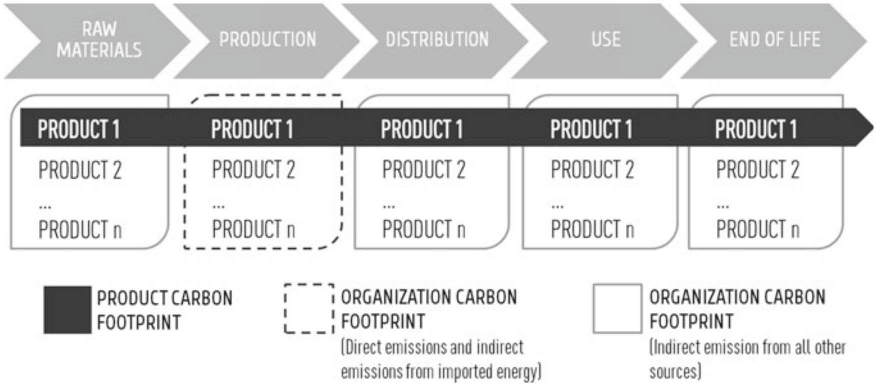


Fig. 1 Organization carbon footprint versus product carbon footprint

need of reporting CF to other business or to respond to consumers needs, different analytical methods for calculating product CF have been developed [56, 60].

The assessment of CF is therefore a strategic tool for companies and, more in detail, it may occur at the organization level (CFO) and also at the product level (CFP). The main difference between CFO and CFP clearly lays in the focus and the boundaries of the study, so that when a CFP is performed only a product is evaluated along its whole life cycle, while when performing a CFO all the products of the company are included in the assessment (Fig. 1). The reference documents for the assessment of CFOs are the GHG Protocol for Organizations [84, 85] and the ISO 14064 [29], that define what an Organization should do to identify, measure and communicate the GHG emissions produced, both directly and indirectly, from all its activities.

The main existing standards and guidelines for the calculation of product CF are, instead, the "GHG Protocol Product Life Cycle Accounting and Reporting Standard", developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the United Kingdom's Publicly Available Specification (PAS) 2050 and the ISO 14067 [29].

The ISO 14064 explicitly refers to "GHG inventory" as the "list of GHG sources and GHG sinks, and their quantified GHG emissions and GHG removals" – that is to be considered the correspondent of CFO—while the ISO 14067 defines the CFP as the "sum of GHG emissions and GHG removals in a product system, expressed as CO_2equivalents and based on a life cycle assessment using the single impact category of climate change".

For any further information relating to the calculation of the CFO and to the abovementioned reference documents, refer to the Chapter by Scalbi et al. in this book, while an overview of the relevant documents for CFO calculation is given in the following Sect. 3.

All the CF methods and standards can be applied by companies to demonstrate their environmental responsibility, to improve their climate change performance and to differentiate from the competitors. Moreover, they can be used to respond to increasing consumers needs for more environmentally friendly products and for more climate related information along the production chain [20]. CF standards aim also to identify the most relevant life cycle phases, from a GHG emissions point of view, evaluate improvement potentials and increase the production efficiency.

Nevertheless, the solely use of CF as an environmental sustainability indicator, especially for the development of sustainability policies at both company and government level, can be misleading because environmental problems includes not only climate change but also other important issues, eg. eutrophication, toxicity impacts and resource use. Therefore, the use of only CF can lead to problem shifting, when GHG emissions are reduced but other environmental impacts increase. Policy-makers and companies which develop actions and policy on the basis of the results provided by the solely CF might thus ignore other environmental issues in their decisions, which could prevent the society to obtain a more environmentally sustainable and circular society [87].

3 Product Carbon (and Environmental) Footprint

In the previous Sect. 2, the origin and the general concept of CF has been explained. In this Section, instead, an overview of the methodologies developed to calculate CF of products will be given, without focusing on CF of organizations since, as already stated, this topic is treated in Chapter by Scalbi et al. in this book. Also, an overview of the Product Environmental Footprint methodology proposed by the European Commission is presented.

Several different schemes have been developed by national and international standard associations to calculate Carbon Footprint; while the name of the indicator is the same, the methodology can vary depending on the system adopted.

The PAS 20,250 was developed by the UK's Carbon Trust in 2008. The Carbon Trust is a publicly funded company, established by UK government in 2001, which aims to support companies and organisation transition towards a low-carbon economy. In those years, the Carbon Trust started an initiative to develop a robust and consistent standard for the assessment of GHG emissions throughout product life cycle, the Publicly Available Specification (PAS) 2050, in order to respond to market needs for more sustainable products and to inform all the stakeholders about product CF The PAS 2050 was published by the British Standards Institution (BSI) and co-sponsored by the Carbon Trust and the UK Department for Environment and is one of the first examples of the will to adopt the use of a single indicator to compare products for the assessment of the life-cycle GHG emissions of products. The standard has developed a framework to quantify GHG emissions of products life cycle and is based on ISO LCA method, focusing only on climate change impacts. More in detail, PAS 2050 can be applied to several products and it defines requirements for the development and application of "supplementary requirements" for specific product categories. A revised version of the standards was published in

2011, consistent with the GHG Protocol Product Standard about specific issues, such as the sector/product rules, biogenic carbon, recycling, land-use change, delayed emissions. PAS 2050 provides guidelines for the consideration of both common methodological topics (e.g. system boundary definition and allocation) and specific issues (e.g. carbon storage and delayed emissions). Anyway, PAS 2050 does not develop specific product or sector rules, but recommends the development and use of sector specific requirements, called "supplementary requirements" which are documents that provide directions, requirements, and guidelines to develop an equivalent assessment for single groups of products, [11, 23, 47, 56]. In 2011 the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) published the Greenhouse Gas (GHG) Protocol Product Life Cycle Accounting and Reporting Standard for the calculation and reporting of product CF. It is based on ISO 14040 series adopting a life cycle approach, and PAS 2050 (BSI) regarding key topics like the way to deal with biogenic carbon, land-use change and delayed emissions. The standard is addressed to companies and organisations in all economic sectors. This guideline allows companies to quantify six GHGs defined by the Kyoto protocol and provides general guidance and more specific guidelines for the quantification and reporting of product GHG emission inventories, called "product rules". In this way, companies can evaluate the product's GHG inventory and possible emission reductions in a certain time period. The GHG protocol can be used also for product comparison: in this case, additional requirements are provided for a certain product category, developed by a group of stakeholders interested in a specific product category [56]. The aim is to quantify and publicly report an inventory of GHG emissions and removals associated with a specific product also providing many practical examples. Product rules are promoted to allow a comparison between products [11, 23, 47].

In 2013 ISO published the ISO/TS 14067, revised in 2018, this Technical Specification provides requirements and guidelines for the quantification and communication of the CF of products, it is based on other ISO standards like Life Cycle Assessment (ISO 14040 series) and on environmental labels and declarations (ISO 14021, ISO 14024, ISO 14025) adopting also product category rules (PCR) developed in accordance with ISO 14025. ISO/TS 14067 also outlines specific requirements on specific issues relevant for carbon footprints like carbon uptake, land-use change, biogenic carbon emissions and soil carbon change. This Technical Specification aims at a quantification and communication clear and unique avoiding the so-called greenwashing and provides specific requirements for GHG emission removals.

Following this will to simplify the communication of the environmental performances, the environmental product declaration (EPD) system introduced the Climate Declaration. The procedure to obtain a Climate Declaration is the same of an EPD, ISO 14040 and 14044 standards for LCA methodology and ISO 14025 standards for environmental declarations, but the result is focused on greenhouse gas emissions. The strength of this methodology is the presence of product category rules and a well-known and internationally recognized EPD program [11, 23, 47].

In general, all the considered systems want to provide the practitioner with instruments functional to obtain a significative and comparable result. Methodologically the approaches described are all based on the ISO 14040 series, a common problem in the use of results to compare products is that the framework described in the standard leaves the individual practitioner with a wide range of choices that may affect the correctness of the results of the study. As we have seen, one of the solutions adopted to overcome the problem is the implementation of product category rules, with a more general approach, in 2010 the European Commission—Joint Research Centre—Institute for Environment and Sustainability published the International Reference Life Cycle Data System (ILCD) Handbook (Joint Reasearh Centre, 2010). The Handbook wants to provide technical guidance for detailed Life Cycle Assessment (LCA) studies and for all that methodologies based on the ISO 14040 and 14044 standards like Ecolabels or Carbon Footprint. It consists in a series of detailed technical documents, providing guidance for good practice in Life Cycle Assessment in business and government. In particular, the Recommendations for Life Cycle Impact Assessment in the European context handbook (Joint Reasearh Centre, 2010). reviews existing environmental impact assessment models and factors to define levels of maturity and define a set of indicators chosen for their strength and quality. In the guide the Carbon Footprint is indicated as Climate Change and the model suggested for the calculation is the Baseline model of 100 years of the IPCC for its wide consensus for characterization at midpoint level in LCA.

At a European level, the objective is to find a common voluntary methodology that can be representative for the categories of products, different Carbon Footprint systems have been tested and the result was that to provide a complete information for consumers on the environmental performance of some group of products not GHG emissions but other environmental impacts are the most significant. The consequence is the need of developing a harmonized environmental footprint methodology that can be unique, representative and that comprise a set of relevant environmental performance indicators. In the Communication to the European Parliament and the Council, Building the Single Market for Green Products, facilitating better information on the environmental performance of products and organizations, the Commission proposed the Product Environmental Footprint as a common method of measuring environmental performance. PEF requires a full life cycle assessment and define a set of relevant environmental performance indicators.

In 2010 JRC published the Analysis of Existing Environmental Footprint Methodologies for Products and Organizations: Recommendations, Rationale, and Alignment, a systematic comparison of main Footprint methodologies available; starting from that report, Manfredi et al. in 2015 made a review with the aim at spotting the differences between Environmental Footprint methodologies and the PEF, he indicated 10 core criterions: life cycle approach, applicability of results, boundary of the evaluation, multi-criteria evaluation, input data type and quality, solving multi-functionality problems, reporting elements, evaluation of uncertainty and review of the study. Results show differences and common points concerning methodological issues, starting from the more evident like the number of impact categories evaluated, stressing the importance of having a wide range of indicators to better understand the environmental burdens of a product and underling the importance of the Product Environmental Footprint Category Rules (PEFCR) to limit the costs and time necessary to complete the complex assessment required according to the PEF guide. Another important issue identified is the data quality, actually, in the PEF method minimum quality requirements that go beyond the requirement to simply report quality are required considering its use as a decision support especially in a policy context. The result of the review confirms the high consistency of PEF method, concerning the core criterion analyzed, guidelines and directions given, even reducing flexibility minimizing the number of choices and decisions that the user would have to make, allow a high level of reproducibility and comparability between studies [47].

What we are going to do here is to propose our point of view based on our experience and knowledge.

Comparing standardized Carbon Footprint and Product Environmental Footprint, the common points are plentiful, first of all both are based on ISO 14040 series, they consider the wall life cycle of the product. Also, the method to calculate impacts from GHG emissions in all the case is the IPCC.

The first and more important difference between Carbon Footprint and Product Environmental Footprint is the number of impact categories, while the CF is focused on the Climate Change and all the methodology is set to evaluate source and effects of greenhouse gas emissions, the PEF describes the environmental profile of the product using a set of indicators. The main objective to have a single indicator is to simplify the communication to the public, a single number that comprehend a lot of information would have been very useful, the problem is that Carbon Footprint is not always able to be the key indicator in many product categories, this is why PEF has a set of indicators that can be limited in the PEF category rules.

Considering product category rules, they are not mandatory for all the considered l methodologies, like for example in ISO14067, but they are very important to drive the practitioner during the analysis. PEF category rules (PEFCR) go further in this role and suggest also the correct dataset to use when primary data are not available.

A huge work has been made regarding database, the main objective is to furnish users with data with a high level of quality. These because an LCA database can be used in a vast number of evaluations, like in product assessments, development of standards, certification and product labelling, product, process, and system development [57].

In the PEF guide a series of instruction are set to define the dataset quality. It is based on four criteria: Technological representativeness (TeR), Geographical representativeness (GeR), Time representativeness (TiP) and Precision (P). The Data Quality Rating (DQR) result in the average of the categories and is used to identify the corresponding quality level. The overall data quality of the dataset requires the evaluation of each single quality indicator. (PEF Guide revised) The data quality requirements for primary and secondary data are set in PEFCR.

The problem concerning data quality is not new, database contain a vast number of datasets that allow practitioners to model products in software and their quality may vary even in the same database, in PEF method each data used must be evaluated using a data quality matrix while in Carbon Footprint methods, there are not minimum data quality requirements.

The work on data brought to the development of initiative like the Life Cycle Data Network and the European reference Life Cycle Database (ELCD) to make data available to the users. With the Life Cycle Data Network (LCDN), launched on February 2014, different data providers can share their data. This network, with its defined requirements, will ensure data availability and quality and assure interoperability and coherence as well as a convenient basis for comparison of available data [69]. Life cycle inventory datasets from different independently operated LCA databases (nodes) are provided thought an interface where the user can access and find them. Datasets are made available by the Global LCA Data Access (GLAD) network. To participate at GLAD, single nodes have to fulfill a set of requirements like for example a common format and a defined flows nomenclature [57].

The PEF method requires the modelling of product waste by the "Circular Footprint Formula" (CFF), which is a combination of "material + energy + disposal" and includes the production burdens, the burdens and benefits from secondary materials input and output, the energy recovery and disposal. The CF methods do not provide guidance on how to approach multi-functionality at End of Life, with the exception of the PAS 2050 which provide different formulas to be applied in specific contexts and does not consider energy recovery, thus do not account for potential energy credits [47].

PEFCR for a specific product category are developed by Technical Secretariats consisting of technical experts such as companies and industry association (representing over 51% of the total European market for each product category), non-governmental organizations, research centres and universities. The Technical Secretariats are supported by a Steering Committee with representatives from member countries and the European Commission as well as by a Technical Advisory Board for providing technical support to specific methodological issues. On the contrary, Product Rule of GHG protocol and Supplementary Requirements for PAS 2050 are developed similarly to PCR of ISO 14025 standard, i.e. they are based on an open and participatory process developed by companies and organizations in cooperation with other interested parties, institutions involving LCA experts in cooperation with companies or single companies and organizations.

The CF standards allows companies and organizations to obtain an environmental label for the certification of the GHG emissions of their products, but this possibility is currently not available for the PEF, which does not have a real environmental label recognized and certified by a third party.

A further difference is the characterization factors for Global Warming impact category, in particular the global warming potential of fossil methane: according to the PEFCR Guidance, its value is 36,75 CO_2 eq., adjusted from IPCC 2013 using the stochiometric balance. IPCC 2013 uses instead a characterization factor for methane equal to 34 CO_2 eq.

The application of the PEF method can be quite difficult and time-consuming, especially regarding the calculation of data quality requirements and data quality rating and the use of Circular Footprint Formula for the End-of-Life stage. Therefore, the application of this method seems not so quick and straightforward as it was expected to be, if the goal is to involve many companies in Europe, especially SMEs.

The application of CF standards could be more viable for companies, due to the lower specific methodological requirements.

4 The Influence of Methodological Choices on CF Results

Despite CF is a standardized methodology, different methodological choices can lead to a difficult comparison of the results. In this paragraph the main critical issues in defining the CF model are discussed. Harmonization initiatives should be evaluated to enhance the comparability of CF case studies through the use of consistent methodological choices.

4.1 Selection of Functional Unit

Definition of the functional unit is a key aspect in a CF study because it allows to compare the results of different but functionally equivalent systems.

The existing CF methodologies provide similar guidance for the selection of the functional unit, but none of them suggest functional units for specific products. For example, ISO/TS 14067 suggests "Where relevant PCR or CFP-PCR exist, they shall be adopted" and "If CFP-PCR are adopted for the CFP study, the quantification shall be conducted according to the requirements in these CFP-PCR".

The influence of the choice of functional unit on CF results has been highlighted in different sectors, such as food, biorefinery, and building materials.

In the food sector, Notarnicola et al. [55] point out that yield or area are the most used functional units, even if neither takes into account the true function of the products. At this regard, they highlight that more accurate choices could be based on the nutritional or the hedonistic value of the food. Saarinen et al. [71] suggested that, despite the nutrient content of food could reflect food function better, it is not possible to evaluate food CF based on individual nutrients (carbohydrate, protein, vitamins, and minerals) because CF/individual nutrient vary greatly and randomly. Therefore, recently different nutrient density models have been developed and applied to compare CFs of food products [48, 86]. In particular, Sonesson et al. [77] adopted a functional unit which reflected the nutrient content of each food in relation to the nutritional supply of the diet, in order to consider the nutrient quality in a given dietary context.

Another interesting option could be the one suggested by van der Werf and Salou [82] which is based on the economic value of the product,in this way the product quality is considered in the product price. They found that a mass-based functional unit favors systems that focus on quantity rather than quality while an economic-value based functional unit favors systems producing food products of greater quality.

The difficulties in the selection of the appropriate functional unit in the CF studies of biorefineries are due to their multifunctional nature. Ahlgren et al. [1] identified four different categories of functional units: use of feedstock (e.g. 1 ha, 1 ton of biomass), single product (e.g. 1 kg of product, 1 MJ of product), function of single product (e.g. 1 MJ of electricity, 1 person*km), and multifunctional (e.g. 1 biorefinery). They suggested that 1 biorefinery could be the most suitable functional unit for LCA models of biorefineries with multiple functions. Sills et al. [75] analyzed the influence of three different functional units (1 MJ fuel, 1 kg animal feed, and 1 ha of production area) on the LCA results of an algal biorefinery. An area based functional unit was indicated as the best choice, even if it does not significantly influence the CF results.

In the building materials sector, the effect of functional unit on the LCA and CF results was evaluated for the concrete production. In particular, Panesar et al. [61] compared the LCA results obtained using six functional units with different complexity. They concluded that the global warming impact category is largely influenced by the functional unit and it should capture the concrete's functional performance metrics specific to its application.

4.2 Consequential Versus Attributional Approach

LCA and CF studies can be carried out following two different modelling approaches: consequential (CLCA) and attributional (ALCA). ALCA and CLCA approaches are defined in the UNEP/SETAC guidance on LCA (UNEP/SETAC, 2011) as "system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule" and "system modelling approach in which activities in a product system, are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit", respectively. Thus, ALCA allows to calculate the CF of the processes used to produce, use and dispose of a given product while CLCA evaluates indirect effects arising from changes in the level of output of the product, defining a cause-effect relationship between a change in demand and the related changes in supply. However, CF standards, such as ISO 14067, do not define which approach is considered or if it is recommended to include the system-wide change in emissions due to a variation in demand for the product. In literature, several studies were carried out to evaluate how the different modelling approaches affect the GWP of a product.

Kua and Kamath [39] analyzed the GWP impact of replacing concrete with bricks in Singapore. They found that while, using ALCA approach, the GHG emissions increase due to the highly energy intensive process of brick manufacturing, with the CLCA such substitution might result in small reductions in GWP because the domestic changes in demands for concrete and bricks produce a change in the imports of these products.

Also in the building materials sector, Kua and Lu [40] evaluated the impact of the modelling approach on the CF results of replacing tempered glass with polycarbonate at different percentages in the Singapore building industry. This study determined how the changes in the import demand of raw materials for tempered glass and polycarbonate production, due to the increase in the market share of polycarbonate, affect the CF of both materials over long term. The results highlighted that replacing tempered glass with polycarbonate does not produce significant changes in terms of GHG emissions with ALCA approach, while under the long term consequential scenario, when the import of both materials respond consistently to the change in demand in Singapore, the replacement causes a substantial increase in GHG emissions.

In general, the influence of the selected approach on the CF results has been also demonstrated in other research fields, such as biofuels [67], electric versus internal combustion engines [10] and milk production [13], revealing that its choice should be carried out on the basis of the LCA aims and clearly stated.

4.3 Impact of Land Use Change Emissions

In the CF analysis of agricultural and forestry commodities, an important source of GHG emissions is related to the carbon stock changes due to land use change (LUC), that is the conversion of land from one use to another use. In particular, carbon emissions can be released directly (dLUC), accounting the conversion of the original land use, or indirectly (iLUC), when current agricultural or forest production is shifted to other areas which causes dLUC there. Since dLUC occurs within the system boundaries of a given product, it can be included into the ALCA system model while the inclusion of iLUC effects implies the shift towards the CLCA model. All the CF standards, ISO/TS 14067, PAS 2050, and the GHG Protocol, are in agreement that LUC emissions should be accounted for in a product's CF if they are due to a change in land management within a studied product system [51]. On the other hand, none of them provide the accounting of iLUC emissions because of the lack of a consensus methodology.

As regards the dLUC emissions, in the ISO/TS 14067 the calculation is based on the IPCC Guidelines [28] which consider the direct changes in four carbon pools (above ground biomass, below ground biomass, litter and deadwood, and soil carbon stock); however, estimates of the size of these pools and the related changes typically involve substantial uncertainty. Furthermore, another critical key hypothesis is the amortization period used for LUC emissions, that is the period over which the GHG emissions are linearly distributed for accounting [5]. IPCC Guidelines, as well as the European Renewable Energy Directive (RED) [18], recommend to assume a time horizon of 20 years, dividing LUC emissions equally across years. However, this assumption does not reflect the real dynamics because the LUC disturbance generate immediate GHG emissions, when associated to above and below ground biomass, and long term GHG emissions, when associated to the soil [66].

The inclusion of dLUC is essential when the CF analysis concerns food, feed and bioenergy products because it could deeply change final value of GHG emissions [65]. Moreover, this remark is more relevant for developing countries than developed countries due to the significant increase of land intended for agricultural use. Maciel et al. [45] highlighted the importance of dLUC inclusion in the CF analysis of soybean cultivation in Brazil, showing that the GHG emissions increases up to 205% when the contribution of carbon emissions from the transformation of 15.4% of land from grassland to farming is considered. Papong et al. [62] evaluated the GHG emissions of bioethanol production from cassava and molasses in Thailand, excluding or including dLUC effect according to two different scenarios (land transformation from perennial crop to annual crop and from rice field area to annual crop). Results showed that dLUC emissions can increase the CF of bioethanol from 10 to 73% depends on the considered scenario.

The assessment of iLUC emissions is an even more challenging mission due to the influence of the employed model, input data, spatial coverage and scenario assumptions. Among the different approaches, the one elaborated by Schmidt et al. [73] is one of the most interesting which is based on the assumption of perfect elasticity in the markets for products dependent on land use and it avoids the amortization of the GHG emissions by using discounted Global Warming Potentials (GWPs). The iLUC issue is mainly felt in the biofuels sector due to the expansion of energy crops in response to increased biofuel demand. At this regard, the European Commission has included the iLUC emissions in the RED [18], by defining a single factor by type of crop. However, this approach is too simplified as suggested by Garrain et al. [24] who proposed origin-dependent iLUC factors. In particular, they analysed the iLUC impacts caused by an additional demand of biofuel in Spain, showing different values of GHG emissions of biodiesel and bioethanol from iLUC depend on where the biofuel is produced.

4.4 Impact of Temporal Dimension

4.4.1 Time Horizon

It is well-known that the results of a CF study are significantly influenced by the choice of time horizon in the GWP. Typically, in literature the most used time horizon of the GWP is 100-year, maybe because it was the middle value of the three time horizons (20, 100, and 500 years) analyzed in the IPCC First Assessment Report [46]. Time horizon is the time over which the radiative forcing have to be integrated, therefore a 20-year and 500-year time frames are used to evaluate short and long term environmental effects, respectively. However there is no scientific reason to choose 100 year time scale than the other two. Lueddeckens et al. [44] reviewed that the definition of the time horizon is a subjective decision and it depends on the goal and scope of the analysis and the interests of stakeholders of the CF study. De Rosa et al. [70] analyzed the influence of time horizon on the GHG emissions from the production of sawn spruce timber in Sweden, demonstrating that 20-year time frame causes an increase in GHG emissions from 502 kg CO_2e/m^3 of structural spruce timber (100-year time frame) to 3220 kg CO_2e/m^3. For this reason, Ocko et al. [58] encourages to report both time horizons, mostly due to the much higher CO2e emissions of CH4 over 20 than 100 years.

4.4.2 Dynamic Carbon Footprint

The variable time in the CF or LCA analysis plays a fundamental role because it can be considered at different levels, leading to a wrong estimation of the impacts. In particular, two areas can be considered priority: the Life Cycle Inventory (LCI), by clearly assuming the temporal profile of emissions, and the Life Cycle Impact Assessment, by using time-dependent characterization factors for GHG emissions taking into account the exact instant when the emissions occur [9].

In the conventional approach, steady-state (static) conditions are assumed and inventory data are aggregated directly without considering their temporal differences and disregarding their potential variation over time. The limits of this approach are amplified when biogenic carbon and long life cycles are analyzed [35]. Pignè et al. [64] identified two different approaches to include temporal aspects in the LCI. In the first one, the practitioner does not built any dynamic model but defines several scenarios with different LCIs, happening at different times of the life cycle. In this way, each scenario is built when substantial changes occur in the mass and energy flows and it is related to a given time period. This approach allows to take into account changes in foreground processes while it is much more difficult to consider modifications in background processes. The second approach aims to allocate the processes, flows, and LCI of a given system over time, on the basis of the evidence that the linked processes of the life cycle are time-deferred. In particular, Pignè et al. [64] developed a temporal database in order to include full temporalization of background system, highlighting that temporal differentiation of the LCI, and especially of the background processes, can significantly change the overall results.

This issue is particularly significant for the buildings which are characterized by long life cycles (usually 40–70 years) and are characterized by time-dependent parameters [54]. Negishi et al. [53] identified the main time-dependent characteristics of a building system related to the building technology level (performance degradation over time, replacement and use of new technologies, inclusion of biogenic carbon), end-user level (occupancy behaviour), and external system level (energy mix, regulations).

In a fully dynamic CF, it is necessary to consider also dynamic characterization factors of global warming. In a static analysis, a unit emission released today is assumed to have the same impact of a unit emission released decades later. However, the radiative forcing of a unit mass pulse emission differs considerably over time [43]. In the last years, different metrics have been proposed to take into account time effect of GHG emissions which also allow to count CO_2 uptake and biogenic emissions. Kendall [36] proposed a new metric, named Time-Adjusted Warming Potential (TAWP), which considers the difference in global warming effect over a specific time between an emission occurring in the future and an emission released today. Levasseur et al. [43] calculated dynamic characterization factors for 1-year time steps, using radiative forcing as a physical parameter without the definition of any fixed time horizon. Negishi et al. [53] adopted time-dependant climate change metrics, such as instantaneous radiative forcing, cumulative radiative forcing and global mean temperature change, which are based on the IPCC models [27]; in this way, the result of the CF study is not a single indicator, as in the static approach, but different values of indicators as a function of time.

Obviously, it is difficult to compare the CF results obtained with static approach with that calculated with dynamic models, first of all due to the major differences in the nature of the indicators. Negishi et al. [53] tried to compare conventional and dynamic LCA of several building components in terms of GHG emissions, revealing that the difference can be very considerable, especially when the biogenic carbon is included in the LCI.

5 Analysis of Available CF Calculation Tools

Carbon Footprint (CF) has become a mainstream environmental indicator in recent years, due to the growing and pressing issue of climate change, and interest in calculating carbon impacts of different subjects and activities has significantly grown. As a consequence, CF calculators have been developed with several different focuses (such as nations, organizations and individuals), being developed both for public and private use.

Available CF calculators differ from each other by a series of features, that are in general the intended users, the goals they intend to achieve, the reference geographical area, the input data required, the calculation methods, the databases used as data sources and the emission factors. Anyway, even if CF calculators can adopt a variety of outlines and approaches, all of them seek to measure the carbon emissions resulting from a given activity or set of activities [83]. Moreover, since they provide estimates of contributions to climate change, CF calculators can play an important role in educating and motivating lifestyle changes geared toward carbon emissions reduction [4].

The aim of this section is to analyze publicly available CF calculators focused on different themes, also through a review of relevant related literature, so to provide an overall insight into the typology of the available tools and the characteristics of the currently used approaches.

5.1 CFO and CFP Calculation Tools

Concerning CF calculators at the corporate level, attention was focused on freely available online calculators which, being in general simple and easy-to-use, can be beneficial for providing preliminary estimations and having a view on GHG emissions for all kind of enterprise (also for those that do not have adequate financial/human resources for detailed calculations or hiring external experts). A summary description of the identified calculators, together with details on the developer and the links to access them, are given in Table 1

All the reported calculators seem to have the ability to well cover the estimation of Category 1 and Category 2 emissions (according to ISO 14064 classification), even if in some cases they do not allow to separate these emissions in specific subcategories. On the other hand, the estimation of emissions falling in the ISO 14064 3 to 5 categories seem to be a little bit more problematic, since some of the calculators cover them only partly (both in terms of covered categories and emissions typologies) and the calculation approaches are quite different. Moreover, most of the calculators are focused only on the calculation of CO_2 emissions and disregard the ones related to other GHG (Fig. 2). For these reasons, most of these calculators can be considered inadequate for detailed assessments of complex production processes (that include GHG emissions other than CO_2) or companies with extended and diverse supply chains, but rather valid for a first insight in companies CFO and useful for temporal comparisons at the level of one company in order to monitor potential improvement.

Five of the abovementioned CFO calculators were compared by Harangozo and Szigeti [25] using a fictitious enterprise and analyzing three different scenarios in terms of its characteristics (different energy consumption and different suppliers activities) in order to have input data. Their findings in terms of results consistency—i.e. in terms of capability to deliver the same or similar result using the same input data—show a relatively low calculators reliability, with differences mainly related to the calculation approaches (consumption—estimated or calculated based on input data) and to different emission factors (based on differences in the country energy mix and because of methodological differences). Scientific literature also includes studies related to the comparison of CFO calculators focused on a specific industry or sector, such as for instance [78], that selected different farm-level carbon accounting tools and tested them using data from a variety of beef production enterprises, highlighting the differences between estimates produced and exploring the reasons behind them. They also underlined that, even where estimates from different tools appear consistent, the breakdown of an estimate may vary independently of variation in the overall results.

The situation of calculators regarding CFP is quite different. In fact, since the CFP quantifies and communicates the amount of GHG emissions across the whole life cycle of a product, it is closely related to the specific supply chain of the product itself and it is more difficult to set out a calculator generally applicable to different kind/categories of products.

Calculators available online mainly offer the opportunity of evaluating the CF related to different food products (see Table 2 for an indicative summary) and thus to dietary consumers' behaviors. All these calculators appears quite simple to use and allow estimations based on low-level data, such as food category, food commodity and quantity purchased. In a few cases it is possible to take into account the emissions related to the origin of the food product and the mode of transportation, but also in these cases the evaluation is based on simple input data (Fig. 3). Kim and Neff

Table 1 Summary of CFO calculators

Calculator	Calculation Features	Link (accessed on July 08, 2019)
Carbon Footprint Ltd	Category 1, Category 2 and Category 3 emissions with a simplified approach	https://www.carbonfootprint.com/businesscarboncalculator.html
Carbon Footprint Management	Category 1, Category 2 and Category 3 emissions with a simplified approach	https://carbonfootprintmanagement.com/free-co2-carbon-calculator/
Carbon Fund	Category 1, Category 2 and partly Category 3 emissions	https://carbonfund.org/take-action/businesses/business-calculators/
Carbon Neutral	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://carbonneutral.com.au/carbon-calculator/
Carbon Trust	Category 1 and Category 2 emissions	https://www.carbontrust.com/resources/sme-carbon-footprint-calculator
Clear	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://clear-offset.com/business-carbon-footprint-2019/
C-Level	Category 1, Category 2 and partially Category 3 emissions	https://www.clevel.co.uk/business-carbon-calculator/
Climate Neutral Group	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://co2-compensatie.nl/en/
Cool Climate Network	Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a good detail	https://coolclimate.org/business-calculator
Green Key	Specific tool for hotel or other type of accommodation. Category 1 and Category 2 emissions, Category 3 and Category 4 emissions with a simplified approach	https://www.greenkey.global/online-hcmi
National Energy Foundation	Category 1 and Category 2 emissions	https://www.carbon-calculator.org.uk/
TerraPass	Category 1, Category 2 and partially Category 3 emissions	https://www.terrapass.com/carbon-footprint-calculator
SYKE (Finnish Environment Institute)	Quite detailed calculator (.xls file) for Category 1, Category 2, Category 3 and Category 4 emissions	https://www.syke.fi/en-US/Research__Development/Consumption_and_production/Calculators

(continued)

Table 1 (continued)

Calculator	Calculation Features	Link (accessed on July 08, 2019)
US EPA Center for Corporate Climate Leadership	Quite detailed calculator (.xls file) for Category 1, Category 2 and Category 3 emissions	https://www.epa.gov/climateleadership/center-corporate-climate-leadership-simplified-ghg-emissions-calculator

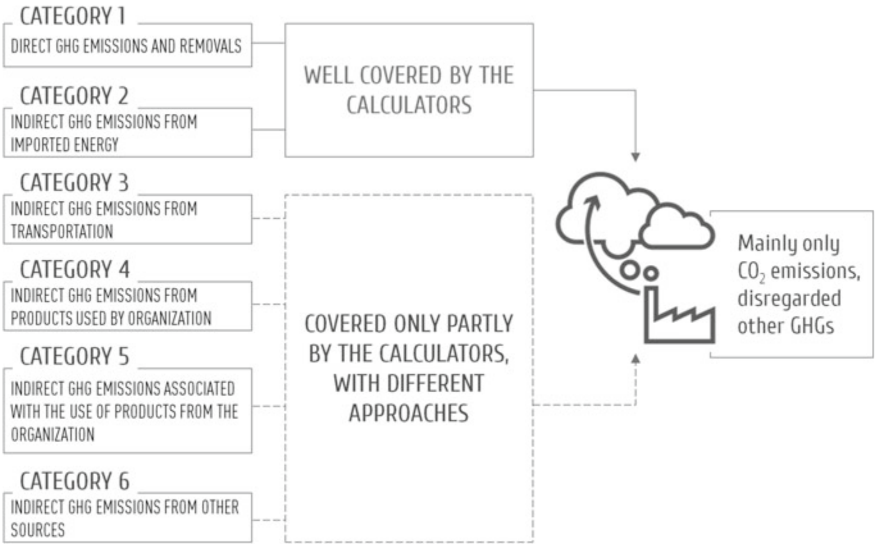
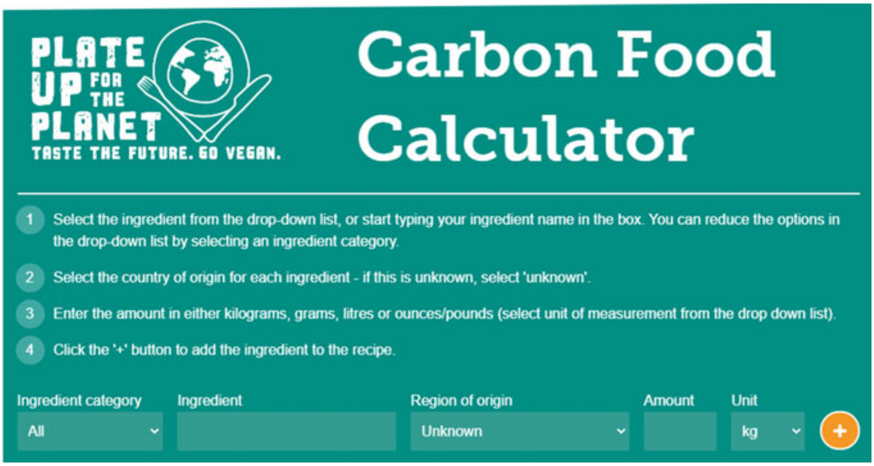


Fig. 2 Brief overview of CFO calculators features

Table 2 Some CF calculators for food products

Calculator	Calculation features	Link (accessed on July 08, 2019)
CelanMetrics	Choice of a food category and a food commodity (evaluated trough a cradle to farm gate approach), transportation by truck and waste production included	https://www.foodemissions.com/Calculator
Eat low carbon	Provision of CO_2 emission for familiar food items, without allowing personalized calculation	https://www.eatlowcarbon.org/
Meals for the Planet	Choice of a food category and a food typlogy	https://meals4planet.org/calculator/
The Vegan Society	Provision of the CF of different menu options, based on the choice of the ingredients and their Countri of origin	https://www.vegansociety.com/take-action/campaigns/plate-planet/carbon-calculator



Carbon Food Calculator

1. Select the ingredient from the drop-down list, or start typing your ingredient name in the box. You can reduce the options in the drop-down list by selecting an ingredient category.
2. Select the country of origin for each ingredient - if this is unknown, select 'unknown'.
3. Enter the amount in either kilograms, grams, litres or ounces/pounds (select unit of measurement from the drop down list).
4. Click the '+' button to add the ingredient to the recipe.

Ingredient category: All
Ingredient:
Region of origin: Unknown
Amount:
Unit: kg

Fig. 3 Example of a CFP calculator data entry interface (https://www.vegansociety.com/take-action/campaigns/plate-planet/carbon-calculator)

[38] reviewed 8 carbon calculators for measuring and communicating indirect GHG emissions from food consumption and included U.S. users among the target audience. Their findings confirm a general lack of consideration of diet-related emissions among CF calculators, under-representing the significance of diet in contributing to indirect GHG emissions, thus highlighting that there is room for improvement and a need for more rigorous methodologies.

Another recent study by in the scientific literature [63], analyzed 18 available calculators (out of 44 environmental assessment calculators identified for agricultural products) conceived for assessing GHG emissions from energy crop cultivation based on CFP approaches. Results of the study show that 9 out of 18 CF calculators were developed for product assessment and that all of them allow an assessment with a “cradle to (farm) gate” approach, while only 8 calculators are able to extend the system boundary to the end of life of the assessed production chain. In conclusion, from the study emerged that calculators address different goals and user groups, with differences in the level of complexity (both in terms of use and data required) and also in the accuracy of results, confirming the abovementioned difficulty to have a calculator generally valid different kind/categories of products.

5.2 Other CF Calculation Tools

Between the available CF calculators regarding study subjects different from organizations and products, the majority is focused on individuals, according to the constantly increasing attention paid to individual behavior as a source of global CO_2 emissions.

These calculators usually divide the individual's profile into common activities and produce estimates on an annual basis through the use of different input data. The simplest calculators allow to obtain a CO_2 emissions value based only on energy-related activities, while more detailed calculators consider lifestyle and/or consumption attitudes (household, food and travel), with also some attempts to provide recommendations on reducing CO_2 emissions.

Scientific literature includes several studies that analyzed and compared individual CF calculators, highlighting the differences between them.

Padgett et al. [59] compared 10 calculators in the United States, founding significant differences in the individual CF estimates despite the use of the same input parameters and thus stressing the need for a higher degree of standardization. Similarly, Kenny and Gray [37] analyzed the inconsistencies and contradictions related to the differences in assumptions, input parameters and methodological aspects (e.g. emission factors used) between individual and household calculators in Ireland, underlining that the available models are able provide estimates rather than accurate measures of CO_2 emissions. Čuček et al. [12] explored different tools for footprints evaluation in their work, identifying CF calculators as the main tools and pointing out that these calculators lack consistency and calculate different results. Birnik [6], reviewing the existing literature, derived a set of 13 normative and evidence-based calculation principles concerning how personal and household carbon footprints have to be calculated, and then evaluated 15 commonly used online CF calculators in order to assess the extent to which they conform to these identified principles.

A summary list of online individual CF calculators, in part also critically examined in a recent study by Mulrow et al. [50], is reported in Table 3.

Analyzing the calculation features of these CF calculators it emerges that the emissions related to home energy and transportation are generally considered (all the calculators collect at least basic information on energy use, and all but one take into account transportation), with a commonly detailing also of air transportation and flight categories. Other emission categories, such as for instance food, water and wastewater are instead less common to the various calculators and, furthermore, additional specific categories (waste and recycling, purchases or consumption activities, etc.) are considered in each one of them. Other common features of the calculators are the advice for lowering emissions and the opportunity to have the breakdown of CO_2 emissions for the different considered categories (Fig. 4).

Salo et al. [72] examined 10 online calculators for non-professional users, focusing the attention on the ones available for Nordic citizens in their own languages and also including two calculators outside these focus regions. They also interviewed 6 calculator hosts to study their expectations and experiences on engaging people to use calculators and to guide consumption. The outcomes of their work show that knowledge intensive calculators are able to reflect lifestyle and activities from an environmental perspective, with tips and pledges are included in calculators to support taking action. However the possibility to engage people in using calculators, especially more than once, is often considered to be a challenge. Salo et al. [72] also point out how calculators' features hold potential for further improvement, as

Table 3 Other CF calculators

Calculator	Calculation features	Link (accessed on July 08, 2019)
Carbon Footprint Ltd	Home energy (by energy sources), transportation (by means of transport, including flights by type) and lifestyle (food, miscellaneous spending and waste)	https://www.carbonfootprint.com/calculator.aspx
Carbon Independent	Home energy (detailed by energy sources), transportation (by means of transport, including flights) and lifestyle (various goods and services based on spending amount)	https://www.carbonindependent.org/
Carbon Offsets to Alleviate Poverty (COTAP)	Home energy use (by US state and energy sources) and transportation (car travel and air travel)	https://cotap.org/carbon-footprint-calculator/
Carbon Solutions Group	Home energy (by US state and energy sources) and transportation (only by car)	https://www.carbonsolutionsgroup.com/carbonfootprintcalc.html
Carbonify	Home energy use (by energy sources), transportation (car, train, air travel) and food consumption	https://www.carbonify.com/carbon-calculator.htm
CarboTax	Home energy use, food, waste, water, transportation, holydays. Based on multiple choice questions	https://www.carbotax.org/
Chuck Wright	Home energy use (by energy sources) and transportation (car, air travel)	https://www.chuck-wright.com/calculators/carbon.html
Cleaner and Greener	Home energy use (electricity, natural gas) by US state	https://www.cleanerandgreener.org/resources/pollutioncalculator.html

(continued)

Table 3 (continued)

Calculator	Calculation features	Link (accessed on July 08, 2019)
Climate Care	Energy (by, energy sources and Country), transportation (car by fuel and flights by type), event (travel and accommodation) and business (energy, travel and freight transportation). Calculation aimed at emissions offseting	https://climatecare.org/calculator/
Conservation Fund	Home energy (by energy sources and Country), transportation (by means of transport, including air travel) and waste	gozero.conservationfund.org/calc/household
Conservation International	Individual and household, events and trips (based on guided choices from pull-down menus)	https://www.conservation.org/carbon-footprint-calculator#/
Empowerment Institute	Home energy use (by energy sources), transportation (car, air travel) and waste	https://www.empowermentinstitute.net/lcd/LCDcalcNet_2012.html
Green Progress	Home energy (by energy sources), transportation (car, air travel) and lifestyle (eating habits and waste)	https://www.greenprogress.com/carbon_footprint_calculator.php
Henkel	Housing (energy by sources and water consumption), nutrition (diet habits and eating out), mobility (by means of transport) and holiday and leisure (travel, accommodation and sports)	https://footprintcalculator.henkel.com/en
Lehigh University	Home energy (by type of home), transportation (by means of transport) and food (eating habits). Tool tailored for students	https://ei.lehigh.edu/learners/cc/carboncalc.html
Michael Bluejay	Home energy (by energy sources), transportation (car, air travel) and food	https://michaelbluejay.com/electricity/carboncalculator.html

(continued)

Table 3 (continued)

Calculator	Calculation features	Link (accessed on July 08, 2019)
My Climate	Home energy (by energy sources), transportation (by means of transport) and lifestyle (eating and shopping habits). Based on multiple choice questions, more detailed calculation provided for household, company, events, flight, car and cruise	https://www.myclimate.org/carbon-offset
Native Energy	Household (by energy sources and US subregions), travel (by means of transport) and events (based on US state, number of attendees and days)	https://native.eco/for-individuals/calculators/
Resurgence	Home energy (by energy sources), transportation (by means of transport, including private flights by type) and lifestyle (dietary choices and food sourcing, leisure activities)	https://www.resurgence.org/resources/carbon-calculator.html
Shrink Your Foot	Home energy (electricity and fuel use) and transportation (car and air travel)	https://store.shrinkyourfoot.org/carbon-footprint-calculator
TerraPass	Home energy (by energy sources) and transportation (car and air travel)	https://www.terrapass.com/carbon-footprint-calculator
The Nature Conservancy	Home energy (by energy sources and US state) and water usage, travel (by fuel typology, including air travel) and lifestyle (eating and shopping habits)	https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/
UN CF calculator	Home energy (by type of housing, energy sources and Country), transportation (by means of transport, including private flights by type) and lifestyle (dietary choices and waste recycling)	https://offset.climateneutralnow.org/footprintcalc
US EPA CF calculator	Home energy (detailed by energy sources and Country), transportation and waste recycling	https://www3.epa.gov/carbon-footprint-calculator/

(continued)

Table 3 (continued)

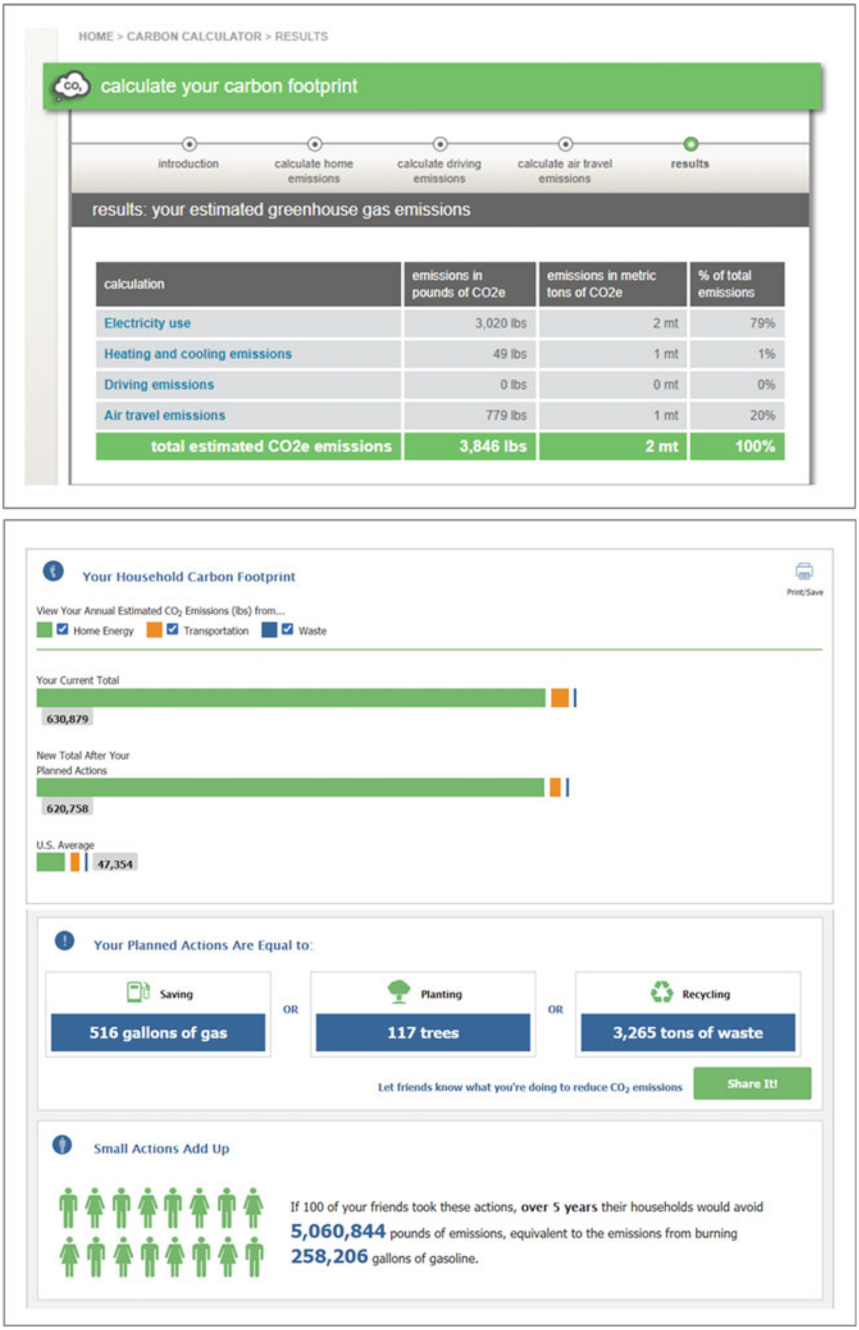
Calculator	Calculation features	Link (accessed on July 08, 2019)
World Wide Fund for Nature (WWF)	Food (eating habits), travel (by means of transport, including flights), home (by type of housing and living habits) and stuff (home items, shopping habits and waste recycling). Based on multiple choice questions	https://footprint.wwf.org.uk/#/

well as have limitations, which should be taken seriously in considering the role of calculators in policy-mixes to steer household consumption.

Specific calculation methodologies/case studies were also investigated in the available scientific literature. For instance, Shirley et al. [74], presented a top-down accounting model for typical households within the US Virgin Islands, using an Economic Input Output calculation methodology based on spending and consumption patterns. The model allows to estimate GHG emissions during the different life cycle phases (extraction, processing, transport, use and disposal) of various commodities and map this to their respective consumption by households, showing electricity use and private road transportation to be major contributors to spending and energy use. Similarly, Isaksen and Narbel [32] calculated CF of Norwegian households, combining a consumer expenditure survey with emission coefficients from an environmental input–output model, that take into account embodied emissions in goods and services, also comparing direct and indirect emissions from consumption activities to the expenditure level of different households.

Regarding individual CF calculators, recent literature also focused on novel calculation approaches, following the idea that real-time evaluations through continuously updated data can be useful to see the effects of lifestyle changes, thus supporting individual action and choices oriented to counteract climate change. Results of previous studies (e.g. [7, 15, 21, 26, 49, 52, 14], in fact, allow to state that general information is ineffective to encourage pro-environmental lifestyles, while personalized information (i.e. information tailored to the receiver's situation, as for instance feedback on the personal energy use/carbon footprints, or specific energy saving tips) allows to obtain better results in encouraging behavioral change.

According to these evidences and ideas, Rahman et al. [68] developed a CF calculator application (named "Ubiquitous Carbon Footprint Calculator") based on an a specific platform (named "Open Carbon Footprint Framework"), that allows users to be aware of their personal CF on the base of their ubiquitous activity and act accordingly. More recently, Andersson [2] presented a mobile application, available for use in Sweden, that estimates users' GHG emissions by means of a hybrid approach based on pairing financial transaction data from the users' bank with environmentally extended input output analysis, claiming it as a new and interesting approach that merits further consideration.



results: your estimated greenhouse gas emissions

calculation	emissions in pounds of CO2e	emissions in metric tons of CO2e	% of total emissions
Electricity use	3,020 lbs	2 mt	79%
Heating and cooling emissions	49 lbs	1 mt	1%
Driving emissions	0 lbs	0 mt	0%
Air travel emissions	779 lbs	1 mt	20%
total estimated CO2e emissions	3,846 lbs	2 mt	100%

Your Household Carbon Footprint

View Your Annual Estimated CO_2 Emissions (lbs) from...

🟩 ☑ Home Energy 🟧 ☑ Transportation 🟦 ☑ Waste

Your Current Total: 630,879

New Total After Your Planned Actions: 620,758

U.S. Average: 47,354

Your Planned Actions Are Equal to:

Saving: 516 gallons of gas OR Planting: 117 trees OR Recycling: 3,265 tons of waste

Let friends know what you're doing to reduce CO_2 emissions

Small Actions Add Up

If 100 of your friends took these actions, over 5 years their households would avoid 5,060,844 pounds of emissions, equivalent to the emissions from burning 258,206 gallons of gasoline.

Fig. 4 Examples of CF calculators results presentation (https://store.shrinkyourfoot.org/carbon-footprint-calculator; https://www3.epa.gov/carbon-footprint-calculator)

6 Conclusion

One of the main global environmental problems is represented by GHG emission by human activities, that constitutes a significant contributor to the global warming issue and the related worldwide negative effects. Consequently, the reduction of GHG emissions has become in recent years one of the main efforts of the international community to cope with global warming thorough strategies towards a climate-neutral world based on initiatives of decarbonisations and resource efficiency policies.

The estimation of the GHG emissions has initially focused on the global and national scales, but it has been gradually turned from this levels to more detailed ones, such as cities, sectors, organizations, products and individuals. As a consequence, a lot of approaches, methodologies and tools, characterized by different levels of feature and complexity, have been developed for CF estimations.

Starting from a general overview on the concept of CF and the main differences between its calculation at the organization and product level, this Chapter focused its attention on the methodologies developed to calculate CF of products, also presenting an overview of other CF-derived footprints and, in particular, of the Product Environmental Footprint methodology proposed by the European Commission. Then, a discussion centered on key aspects such as functional unit, temporal dimension of CF assessment, modeling approaches and specific relevant GHG emission sources, highlighted that the LCA approach is the main used for CF estimation and that there are some critical issues that affect the CF calculation model. The subsequent analysis of publicly available CF calculators supported by a review of relevant related literature, provided an overall insight into the different typologies of tools and the characteristics of the currently used approaches, confirming the already cited change of focus of CF (calculators tailored for individuals activities and lifestyle resulted the most widespread).

Given the above, the following considerations can be made as a conclusion of this Chapter.

- LCA-based estimation represent the most used approach to calculate CF. However, some critical issues are intrinsic in the definition of CF calculation model and, despite CF well standardized as a methodology, different methodological choices can lead to a difficult comparison of the results. Therefore, critical issues have to be faced and harmonization initiatives should be evaluated to enhance the comparability of CF case studies through the use of consistent methodological choices.
- LCA-based estimation, as indicated by various research results (see Udara Willhelm [80]), neglect several uncertainties and this may result in a relevant variation of actual emissions and predicted emissions. Therefore, it is desirable that new calculation approaches aimed at facing this issue will be explored. In this regard, Udara Willhelm Abeydeera et al. [80] propose discrete event simulation and system dynamics as newer approaches and also suggest the integration of information technology related tools (such as Building Information Modelling

  and machine learning) as a possible way to support global researchers in a more effectively estimation of emissions.
- There is a lack in the practical utilization of research outcomes on CF as a basis to understand the current situation of GHG emissions and consequently implement effective action plans. Thus, it is crucial to fill this gap between the research and practices, employing research to estimate CF, but also to identify and implement reduction/mitigation strategies.
- As observed, the perspective of CF analysis has been gradually turned from the "macro" to the "micro" level and, in this context, it is acknowledged the significant role that individuals are playing and will play. Moreover, citizen engagement in science and policy-making is becoming more and more central in policies and strategies. At the EU level, in particular, the importance of more citizen engagement has been recognized and strengthened in the Lisbon Treaty with the European citizens' initiative and in a number of documents and political declarations, such as the Commission contribution to the Sibiu Declaration for a "new strategic agenda for the EU 2019–2024". In such a context, therefore, the promotion of research regarding individuals CF represents a key aspect to provide a scientific basis for developing a low-carbon economy.
- Today's efforts to combat climate change have focused mainly on specific sectors/actions, such as for instance transportation or energy production and consumption (with the significant role of renewable energy and energy-efficiency measures). However, in order to meet emission reduction targets it is also necessary to tackle other emissions and, as already well stressed, products have consequently become one of the main focus of CF calculation. In this regard the Circular Economy represent a unique opportunity to help tackle the climate crisis by reducing GHG emissions along supply chains, preserving the embodied energy of products and materials and increasing carbon sequestration through the regeneration of natural systems [17]. It is therefore crucial to strengthen research on the nexus between CF and Circular Economy actions, also integrating CF with other tailored indicators in a specific circularity measurement scheme.

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Carbon Footprint of Food Waste Management: A Case Study in Rio De Janeiro

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Abstract The negative effects of municipal solid waste management to the environment are associated with greenhouse gas (GHG) emissions, especially regarding the biodegradation of the organic fraction of the waste in landfills, which is considered its final destination. With the objective to change this inefficient practice and incorporate the circular economy principals to the solid waste management, the anaerobic digestion is considered to be a promising alternative for the organic fraction treatment. Therefore, this chapter proposes an evaluation of a current and an alternative scenario for the food waste management from a specific case study in Rio de Janeiro, Brazil, considering the municipal large food waste generators, such as supermarkets and street fairs. A carbon footprint analysis was conducted for both scenarios and GHG emissions were quantified. The results indicate emissions of 138.51 t $CO_2e.day^{-1}$ for the current scenario and a reduction of 90% of this total amount by the alternative scenario adoption, with incorporation of an anaerobic digestion treatment unit. Finally, with one-year implementation of this alternative scenario, it is expected to avoid 45,291.33 t CO_2e emissions. Apart from GHG emission reduction, the alternative scenario promotes the circular economy of food waste, with the possibility of

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181,586.32 kg of biosolid and 38,549.26 m^3 of biogas production, which are valuable products that can be used as a resource for supply wholesalers and retailers activities demands and on agriculture production.

Keywords Food waste management · OFMSW · Carbon foot print · Anaerobic digestion · Biogas · Renewable energy

1 Introduction

The worldwide growth of municipal solid waste (MSW) is estimated to be around 2 billion tons per year, according to UNEP and ISWA [41] and its composition depends on the geographic region, economic activities, climate and social condition, living standards and eating habits of the population and waste management strategies [32]. The organic fraction of municipal solid waste (OFMSW) comprises a larger percentage 50 to 70% of the MSW in low-income countries, while in high-income countries they typically account for 20 to 40% of the MSW [41]. The OFMSW is generated by different sources in urban areas, such as food supply centers, supermarkets, restaurants, household kitchen, yard trimming, among others. Because of these characteristics, which varies regionally and nationally [5], the management and treatment of OFMSW become a big challenge.

The negative effects of inadequate solid waste management to the environment are known and disseminated all over the world, especially regarding the waste final destination [29, 41]. Uncontrolled diffuse methane emissions and leachate production are some of the main problems arising from organic waste landfill [42]. The Intergovernmental Panel on Climate Change (IPCC) estimates that greenhouse gas (GHG) emissions from the waste management sector represent about 3% of global emissions [41]. However, that estimative is limited to the last stage of the waste management chain, related to final disposal of the waste. Therefore, it does not include transport and logistics emissions, nor the total amount of GHG emitted during the entire life cycle of food products, from their production to consumption, taking into account the use of energy, water and land they have demanded during lifetime. Recent studies have stated that if food wastage were a country, it would be the third largest GHG emitting country in the world [20]. The total carbon footprint of food produced and not consumed is estimated at 3.3 Gt CO_2e, without accounting for GHG emissions from land use change [20].

In addition to the GHG emission problems inherent in waste landfilling, new sites for implementing landfills are becoming increasingly scarce in urban areas, so this waste final disposal practice is now facing a great challenge in the cities. In this scenario, technologies for the OFMSW treatment and resource recovery are needed to ensure the sustainability and resilience of cities. The composting process is an alternative; however, it also requires a considerable area for treatment, while energy consumption for controlled aeration is intense. Thermal incineration, which can reduce a considerable volume of MSW, has several drawbacks for the OFMSW treatment, mainly associated with the high moisture content of the waste. The requirement of an external supply of oxygen, a well-equipped burning system and appropriate pollution control accessories make the implementation of this process more difficult [8]. It is also important to mention that, in the case of thermal treatment, the process releases to the atmosphere an amount of carbon from the burning, differing from the regenerative and biogenic emission sources, such as composting and anaerobic digestion of organic waste.

Several studies addressing the life cycle of municipal solid waste have considered the anaerobic digestion (AD) a sustainable process for treating the OFMSW [9]. This is because AD contribute to the mitigation of GHG emissions and allow resource recovery from by-products, such as biogas (that can be transformed into electricity and thermal energy or used as biofuel) and biosolids (that can be used in agriculture or soil recovery), ensuring the resilience of cities on the circular economy approach.

Considering this scenario, this chapter is intended to provide insights of the management of large-scale food waste generation, such as supermarkets and street fairs, and its impacts in the City of Rio de Janeiro, Brazil. The environmental and economic benefits associated with the first semi-industrial scale solid-state AD (SSAD) of OFMSW in Latin America is also evaluated. Located at the EcoParque-Caju of the Municipal Urban Cleaning Company (COMLURB), the unit recovers biogas in the form of energy by a combined heat and power (CHP) system and also produce biosolids for community gardens and farms use [31]. It is worthy to mention that, considering the fact that the landfill is located 80 km far from EcoParque-Caju, this SSAD process avoids the transportation and landfill disposal of the food waste.

The carbon emissions arising from the food wastage, based on the waste composition (food types treated) and level of the food chain in which the waste has occurred, as well as the carbon emissions from food waste management, are also assessed in this chapter. From the carbon footprint quantification, it will be possible to evaluate the contribution of some initiatives such as the development of strategies to reduce food wastage and the incorporation of AD in food waste management, in order to mitigate GHG emissions and promote resource recovery from the by-products, in a circular economy point of view.

Apart from this introduction, this chapter is organized as follows. A review of the carbon footprint of food waste management is presented in Sect. 2, with the characteristics and worldwide food waste contextualization. Section 3 is dedicated to the carbon footprint methodology applied for this study regarding the different evaluated scenarios while the characteristics of the case study are presented by Sect. 4. Section 5 shows the main results and discussion and finally Sect. 6 presents the main conclusions.

2 Carbon Emissions from Food Waste Management

Because of human lifestyle in urban areas and considering the continuous growth of world urban population, these regions are increasingly becoming points of intensive consumption of goods and services. The scenario for food is not different, with increased consumption and wastage. According to [19], approximately one third of all food produced for human consumption is lost or wasted along the food chain, considering the food production by agriculture, storage, trade, transport, distribution and consumption processes. As defined by FAO [20], the term “food wastage” encompasses the food loss during agricultural production until distribution in the wholesale market stages, and the food waste which is generated from retail market until its final consumption.

Along with the food wastage comes the environmental impacts of its management until its final destination in landfills. FAO [20] estimates that upstream steps, including agriculture production, post-harvest handling and storage comprise 54% of the total food wasted food, followed by the downstream processes with 46%, which include processing, distribution and consumption. As a result, the United Nations aims to halve the food waste produced at the retail and consumer levels by establishing the United Nations Sustainable Development Goal (SDG) 12.3 [40].

Regarding the impacts of GHG emissions, a large part of the processes responsible for these emissions comes from the agricultural production level, although expressive amounts come from later levels in the value chain. Therefore, it is estimated a total of 3.5 Gt CO_2e of GHG emissions from food waste and a cost of USD 394 billion in damages per year, based on the social cost of carbon [19]. Moreover, the commodities that most contribute to the carbon footprint by world region are cereals, meats and vegetables, counting for more than 60% of carbon footprint [19]. Specifically, in the context of Latin America, milk, meat, vegetables and grains count for the agricultural commodities with the highest GHG emissions costs for the society.

Although waste prevention is the highest priority in waste management hierarchies, some food wastes are inevitably generated due to the lack of efficiency at consumption level [39]. For this case, a sustainable alternative treatment is being increasingly required to change the traditional processes applied worldwide to a circular economy management approach.

Following this idea, Slorach et al. [39] have assessed the environmental and economic sustainability of five 2030 scenarios for the management of household food waste in United Kingdom in comparison with the current situation. The scenarios considered a different share of four widely used treatment methods: anaerobic digestion, in-vessel composting, incineration and landfilling. They found that there are significant carbon emissions reduction associated with the treatment of food waste via AD technology compared to landfilling and affirmed that separated collection of food waste should be encouraged. However, waste prevention is still the best way to achieve significant environmental and economic savings, allowing to save 3.2 Mt CO_2e per year.

To evaluate the advantages of investing in AD treatment, Chen et al. [9] assessed the environmental and economic analysis through a quantitative and comprehensive evaluation of food waste, which was conducted in food waste-based methane plant located in China. When only methane production was considered, the net energy output (186.01 MJ) was slightly higher than the net energy input (167.47 MJ), implying that AD was a clean energy producing technology. Besides, they indicate the global warming potential (GMP100) of 96.97 kg $CO_2e.t^{-1}$ of food waste treated.

Fan et al. [17] evaluated the carbon footprint of organic waste treatment by reviewing pre-treatment and post-treatment approaches which complement the AD process in order to ensure the desired quality of biosolids and biogas, as by-products. The carbon footprint was calculated based on energy consumption and considered the processes pre-treatment, digestion process, post-treatment, waste collection and transportation. They concluded that, for the AD operation to be sustainable, the sum of the benefits by the utilization of biogas and biosolids needs to overcome the impacts from total AD operation, including the pre-and post-treatment and the transportation activities.

In order to deeply evaluate the carbon footprint of food waste, Scholz et al. [38] applied this approach to a case study in Swedish supermarkets. This carbon footprint analysis is conducted from cradle up to the retail stage of the food supply chain, including delivery. The results indicated a wastage of 1570 t of fresh food (excluding bread) in the six supermarkets, which has a carbon footprint of 2500 t CO_2. The fruit and vegetable and the meat departments contributed to 46% and 29% of the total carbon footprint of food waste, respectively.

On the same hand, Marrucci et al. [30] evaluated the environmental performance of an Italian supermarket waste management system, through its carbon footprint and compared the environmental impacts in terms of CO_2e of different waste treatments for each waste category. They found that anaerobic digestion releases less GHG emissions and this type of treatment is a great initiative to significantly reduce the environmental impact of a retail supermarket.

Moreover, it is worthy to mention some studies addressing the GHG emissions analysis not only related to the organic fraction of MSW but for all the MSW management of a city. In this respect, Itoiz et al. [27] presents the “Zero Waste” tool, called CO2ZW, which produces a GHG emissions inventory from MSW of Mediterranean European countries. This tool considers the key stages and parameters for the GHG emissions calculation and follows the IPCC guidelines for national inventories, which is based on life cycle assessment (LCA) principles. The authors indicate that, with the CO2ZW tool, it is possible to evaluate the waste management infrastructures and policies, along with the quantification of GHG emissions from MSW management activities. Because of that, the GHG emissions quantification is essential to guide solid waste policy and climate change solutions.

Pérez et al. [33] applied the carbon footprint based on LCA approach to calculate the GHG emissions from the MSW treatment stage using Madrid City as a case study. The methodology takes into account the direct GHG emissions produced in waste treatment, the indirect GHG emissions related to the use of electricity, and the avoided GHG emissions as a result of the use of by-products from MSM treatment in substitution of raw materials in a production chain. The current treatment stage, with a carbon footprint of 224 kg CO_2e/t_{waste}, was compared with several alternative scenarios for solid waste treatment. The authors concluded that the scenarios based on total recovery of by-products from waste-to-energy or anaerobic digestion treatments present the lowest carbon footprint.

Ali et al. [1] used an energy approach to evaluate the environmental footprint of solid waste management alternatives in Gujranwala city, Pakistan, with the perspective based on LCA. This methodology outputs the direct GHG emissions from fossil energy consumption, waste digestion and combustion, as well the net GHG emissions, which is calculated based on direct emissions minus the emissions avoided by the implementation of the strategies proposed. The study evaluated three scenarios of solid waste treatment and disposal: open dumping; composting and material recycling with sanitary landfill; composting and recycling with incineration. The adoption of composting and recycling for solid waste treatment and the sanitary landfill for final disposal of the waste were identified as the best alternatives. The incineration practice, instead of landfilling, results in similar amount of carbon emissions but the first one results in relatively lower stress on the environment.

Islam [26] investigated the GHG emissions of MSW management in Bangladesh through existing and proposed scenarios, by carbon flow model using the annual urban waste generation data. The proposed scenarios considered the landfill gas (LFG) recovery, waste to energy (WtE) and material recovery facility (MRF). For modelling the carbon flows, the study indicates the horizontal and vertical fluxes and, also, the carbon stocks of the processes. The conclusions show that environmental benefits could be nationally and globally achieved with the incorporation of mixed waste incineration and LFG recovery to generate electricity.

Finally, Malakahmad et al. [28] aims to evaluate the GHG emissions of solid waste technologies by assessing the carbon footprint of three proposed scenarios for Malaysia reality: solid waste landfilling with gas recovery; organic waste treated on anaerobic digestion system and recycling of inert solid waste such as plastic, glass and textile; and waste incineration. The study considers the 2006 IPCC methodology for carbon footprint emissions calculation. The results indicated that the highest avoided CO_2e emissions were achieved by the second scenario and landfilling practice produces 0.291 t CO_2e.

Therefore, taking into account the background literature on carbon footprint tools and the obtained results for GHG emissions from food waste management and the incorporation of AD treatment, the methodology applied for the current case study is given in the flowing section.

3 Methodology

Figure 1 shows the food supply chain considered in this chapter and also highlights the boundaries involved, with the food waste and loss being generated in each step.

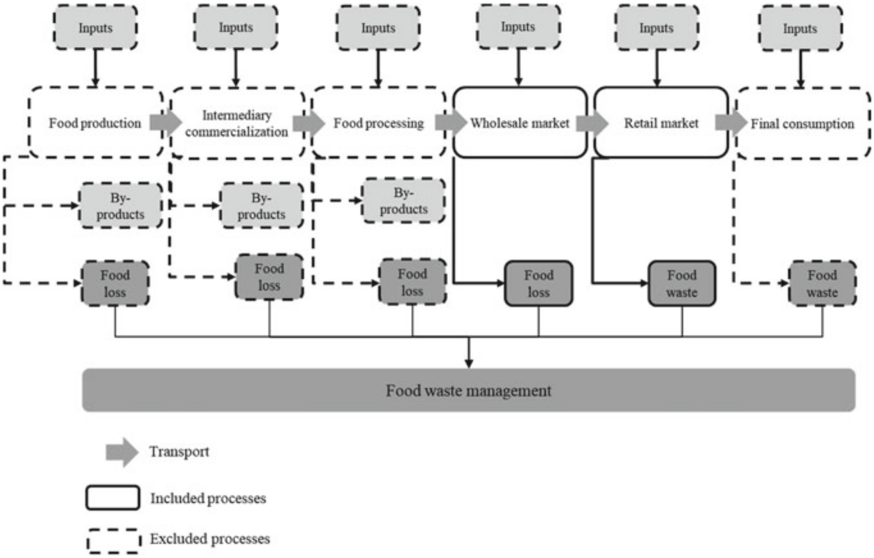

Fig. 1 Food supply chain steps and boundaries. *Source* Based on Behnke and Janssen [3]

From Fig. 1, it is possible to observe the steps of the food supply chain from the food production until its final consumption. Each step is responsible for food waste generation, which has an appropriate management until its final destination in landfills. With the objective of GHG emissions evaluation from large waste generation in urban limits, this chapter provides a carbon footprint analysis of the management steps of food loss from wholesale market and food waste from retail market, as illustrated by continuous black lines in Fig. 1. As it can be seen, the food waste mass generated by large-scale generation establishments, such as gross markets, supermarkets and street fairs are considered, where an AD facility could be an opportunity for decentralized treatment and resources recovery from waste.

Also, this work proposes an evaluation of a current stablished scenario and an alternative one, where the AD treatment technology is incorporated into the food waste management. As suggested by the EU Guide for supporting decisions for waste management [11], because the alternative scenario incorporates a specific type of food waste treatment, which results in a change in the food waste management chain, there is no need for calculation of carbon footprint associated with the steps of the food supply chain.

However, this chapter provides secondary data of GHG emissions based on FAO [18] according to the agriculture production, which presents an estimation for the entire Brazil country in the year of 2017. From the total GHG emissions per each activity of the agriculture sector and the total of each product manipulated, an emission conversion factor was estimated and is presented in Table 1. From that, some agricultural activities emissions are estimated for the state of Rio de Janeiro. Because of the lack of specific data for the city of Rio de Janeiro, it is not possible to estimate

Table 1 Emission conversion factors for agricultural activities

Activity	Emission conversion factor	
	Unit of measure	Value
Enteric fermentation	0.91	t $CO_2e{\cdot}animal^{-1}$
Manure management	0.01	t $CO_2e{\cdot}kg\ N^{-1}$
Rice cultivation	1.36	t $CO_2e{\cdot}ha^{-1}$
Synthetic fertilizers	0.01	t $CO_2e{\cdot}kg\ nutrient^{-1}$
Manure applied to soils	0.01	t $CO_2e{\cdot}kg\ N^{-1}$
Manure left in the pasture	0.01	t $CO_2e{\cdot}kg\ N^{-1}$
Crop residues	0.01	t $CO_2e{\cdot}kg\ nutrient^{-1}$
Cultivation of organic soils	7.48	t $CO_2e{\cdot}ha^{-1}$
Crop residues burning	0.08	t $CO_2e{\cdot}t\ dry\ mass^{-1}$
Savanna burning	0.76	t $CO_2e{\cdot}ha^{-1}$

GHG emissions associated to the agricultural activities and the consecutively food supply chain steps until it arrives at the final consumer.

So, for the evaluation of food waste management carbon footprint, the current and alternative scenarios considered for this analysis are presented in Fig. 2.

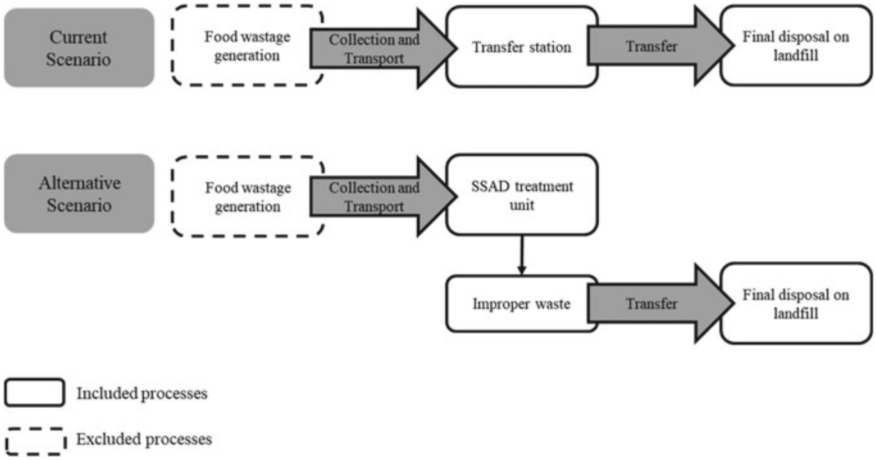

Fig. 2 Current and alternative scenarios

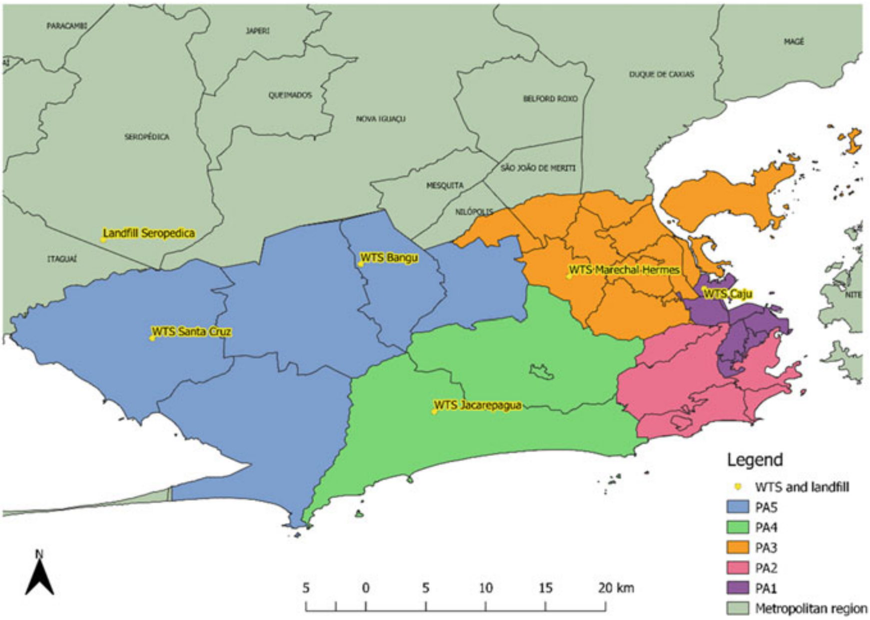

Fig. 3 Waste management facilities location in the current scenario. *Source* Adapted from PMGIRS (2016)

The carbon footprint calculation will follow the methodology presented by EPE [16], which develops a protocol and an *Excel* spreadsheet tool [15] for quantification of GHG emissions from waste management activities. So, as stated in *Excel* spreadsheet, for current scenario, the activities which are considered for calculation are: "Transport and Collection", "Sorting–Transfer" and "Landfilling". For the alternative scenario, the activities are: "Transport and Collection" and "Anaerobic Digestion". It is worthy to mention that the GHG direct emissions are calculated separately per activity and converted in tons of CO_2e for a period of one day, for both current and alternative scenarios. Indirect emissions are not quantified by this study due to the lack of data related to electricity consumption of some activities.

For "Transport and Collection" activity, which is considered in both current and alternative scenarios, the GHG emissions are calculated from road freightage data considering the variables: "vehicle.km", "average fuel consumption" and "emission factor". For the "vehicle.km", the average of travel distance of collection and transfer routes are considered and the number of vehicles in the fleet was calculated based on the food waste mass generated and the vehicle capacities: 10 t for collection truck of wholesalers and street fairs, 5 t for collection truck of supermarkets and 28 t for transfer vehicles [10]. Moreover, the fuel consumption of 53.51 L per 100 km is based on Franca [22] and the emission factor of 2.631 kg $CO_2.L^{-1}$ is indicated by Franca et al. [21].

It is important to highlight that, for the current scenario, the food waste mass is considered to be collected, transported and transferred to the landfill in an aggregate way, with the inert waste mass also. On the other hand, for the alternative scenario, a selective collection is considered for the food waste from supermarkets, street fairs and wholesalers, where the food waste is no longer collected together with the mixed waste, but in a selective way. In addition, for the alternative scenario, even though the food waste is separately collected, it was considered a percentage of 15% of improper materials [10] which has low biodegradable for the SSAD treatment. So, the improper materials mass was considered to be transfer until the final disposal at the municipal landfill. However, because of the insignificant biodegradability of these materials, there is no need for quantifying the GHG emissions at the landfill.

On the other hand, for "Sorting – Transfer" activity, the direct GHG emissions from permanent facilities and on-site mobile equipment are calculated based on fuels consumption, which was measured in volume. The amount of diesel which is consumed is estimated according to Angelo [2]. For indirect emissions from electricity use, data are also based on Angelo [2].

In case of the GHG emissions from "Landfilling", this work considers the IPCC (Tier 2) First order decay model [24] and also some characteristics pointed out by CETESB [7] for specific variables of the Brazilian reality, the fraction of methane in landfill gas, methane generation rate constant and biogas oxidation rate. Equations (1), (2) and (3) describes more specifically this calculation.

$$P_{CH4} = \sum_{x} \left\{ \left[(A \times k \times FW_t(x) \times FW_F(x) \times Lo(x)) \times e^{-k \times (t-x)} \right] - R(t) \right\} \times (1 - OX) \tag{1}$$

$$Lo = MFC \times DOC \times DOC_F \times F \times 16/12 \tag{2}$$

$$A = (1 - e^{-k})/k \tag{3}$$

where

P_{CH4} (methane produced)	Calculated
A (normalization factor, dimensionless)	Calculated (based on EPE, 2013)
k (methane generation rate constant, years^{-1})	0.09 [7]
FW_t (total of food waste produced, Gg.year^{-1})	Sum of food waste produced by the case study
FW_F (fraction of total food waste disposed in landfill)	1.0, for current scenario
$Lo(x)$ (potential of methane emission, Gg.Gg FW^{-1})	Calculated

(continued)

(continued)

P_{CH4} (methane produced)	Calculated
t (period of time)	Calculated
x (current time)	Considered to be zero, as the present time
$R(t)$ (methane recovery, Gg.year^{-1})	1.0 (based on CETESB, 2010)
OX (oxidation factor, dimensionless):	0.1 [7]
MFC (methane correction factor, dimensionless):	0.6 [24]
DOC (degradable organic carbon, dimensionless):	0.85 [10]
DOC_F (fraction of DOC dissimilated, dimensionless):	0.5 [24]
F (fraction of methane in landfill gas, dimensionless):	0.5 [7]
molecular weight (CH_4/C):	16/12 = 1.33 [24]

So, first of all, the methane production was calculated based on Eqs. (1), (2) and (3) for a period of one year and then the total methane emissions were calculated discounting the amount of recovered methane, as shown in Eq. (4).

$$E_{CH4} = \frac{(1 - OX) \times (P_{CH4} - R_{CH4})}{d_{CH4}} \tag{4}$$

where:

E_{CH4}(total of methane emissions, m^3·year^{-1})	Calculated
OX(oxidation factor, dimensionless):	0.1 [7]
P_{CH4}(methane produced)	Calculated
R_{CH4}(total of methane recovery, Gg·year^{-1})	1 (based on [7])
d_{CH4}(methane density, Gg·m^{-3})	0.000000657

So, the estimated data of total methane emissions produced in one day was inserted in *Excel* spreadsheet [15], together with total methane recovery, for direct emissions from biogas combustion unit. Moreover, the emissions from permanent combustion facilities and on-site equipment is based on Angelo [2] for diesel consumption, estimated in volume.

Finally, for "Anaerobic Digestion" direct emissions calculation, in case of alternative scenario, the input variables were: quantity of food waste treated (tons), biogas yield, percentage of biogas leakage from bioreactor and its methane content, volume of biogas treated in combustion unit and its methane content and diesel fuel consumption of other on-site equipment. The electricity consumption is accounted for indirect emissions. Data from the garage-type SSAD plant [10], located at the EcoParque-Caju, Rio de Janeiro, are considered for this calculation. Table 2 summarizes the values for all these variables.

Table 2 Variables of anaerobic digestion GHG emissions

Variable	Unit of measure	Value
Biogas yield	$m^3.t^{-1}$ of food waste	101.9
Methane content of biogas leakage	% CH_4	60
Methane content of biogas treated on flare unit	% CH_4	10
Volume of biogas treated on flare unit	% of total of biogas produced	1
Diesel consumption by on-site equipment	m^3day^{-1}	0.35
Electricity consumption	$MWh.day^{-1}$	0.38

Source: Comlurb [10], Ornelas-Ferreira et al. [31] and Angelo [2]

From the calculations presented in this section, the results will indicate the amount of food waste generated by wholesalers, supermarkets and street fairs, and the direct GHG emissions from the food waste management steps until its final destination. Both current and alternative scenarios are applied for the city of Rio de Janeiro, which is considered a case study.

4 A Case Study in Rio De Janeiro

The city of Rio de Janeiro is one of the biggest Brazilian megacities, with a population of 6,718,903 inhabitants, disposed in 941,06 km^2 of urban area [23]. Moreover, the economic and social activities extrapolate the municipal boundaries over the entire metropolitan region, which represents 12% of the state of Rio de Janeiro area and 74% of total population [25].

In terms of municipal solid waste impacts, Rio de Janeiro, the capital of the state that takes the same name, is the responsible for the second large GHG emissions from solid waste disposal, according to CETESB [7]. In the last year measured, i.e., 2005, Rio de Janeiro registered 175.55 Gg CH_4 emissions from solid waste landfilling. Also, the city of Rio de Janeiro responds to 1,574.2 Gg CH_4e in the same year for solid waste disposal in landfills [37]. Moreover, the city has a waste generation per capita of 1.43 $kg \cdot inh^{-1} \cdot day^{-1}$. Taking into account the total population, it is estimated a solid generation of 9,227 $t \cdot day^{-1}$, from which 9.29% corresponds to large waste generation commercial establishments, such as supermarkets and retail markets [35]. Thus, 52% of this amount of refers to organic materials, which corresponds to 4,798.04 $t \cdot day^{-1}$ of OFMSW. However, it is important to point out that this study considers the food waste from the large waste generation establishments such as retail markets, supermarkets and street fairs.

The secondary data investigation allows the evaluation of the food supply chain of the city of Rio de Janeiro, considering the primary producers and intermediary traders until the wholesale and retail markets. The technical supervision company of rural production (EMATER) is the responsible for elaborating reports regarding the total production per each type of food of the state of Rio de Janeiro [13, 14].

Following the food supply chain steps (Fig. 1), at the wholesale stage, CEASA is the main center of food distribution in the state of Rio de Janeiro [6]. There are six units spread around the state area which are responsible for more than 1 million of tons of food commercialized by around 800 companies. The unit located at city of Rio de Janeiro is the second largest food trade facility in Latin America. Besides CEASA, the city has another wholesale market named CADEG, the Municipal Market of the City of Rio de Janeiro, located inside the urban area.

From the wholesalers, the food is transported and distributed to the retail markets and street fairs, the final destination before the individual consumer. The retail markets are represented by the main supermarket companies in the city, as indicated by Rio de Janeiro Waste Management Report [36]. On the other hand, the street fairs are evaluated based on the street fair location report provided by the Rio de Janeiro city hall [34], which is responsible for its commercialization allowance.

In this chapter, it was considered the municipal solid waste management applied for the current scenario. The waste management chain is composed by five transfer stations (WTS Caju, WTS Jacarepaguá, WTS Marechal Hermes, WTS Santa Cruz and WTS Bangu) and the municipal sanitary landfill (Seropédica), as presented in Fig. 3, which also indicates the five planning areas (PA) of the city.

For the alternative scenario (Fig. 2), it was also considered an AD treatment unit which was incorporated into the OFMSW management. For this purpose, data report of biogas and biosolid generation in the first semi-industrial SSAD garage-type system located at ETR Caju area (EcoParque-Caju) was taken into account, with treatment capacity about 30 t OFMSW·day^{-1} (corresponding to about 50 thousand inhabitants. Regarding biogas production, it is estimated a biogas yield of 101.9 m^3.t^{-1} OFMSW, with 76% as the maximum methane content. This amount allows an estimated energy recovery of 3,379 kW per month, that could be used as electric or thermal energy, besides biomethane fuel. On the other hand, the system is able to produce 480 kg·t^{-1} OFMSW of biosolids, which is a stabilized organic material rich in nutrients that has agricultural potential to be used as organic compost or soil conditioner [31].

5 Results and Discussion

Considering the first step of the food supply chain, which is the primary production, the city of Rio de Janeiro is supplied by the entire state of Rio de Janeiro, which has the majority (78% of the total food production) of fruit and vegetable, corresponding to 9,379.53 t·day^{-1}. Considering the last years with available data (2018 and 2019), animal-derived products, such as milk and eggs, were responsible for 10% of the total food produced (12,049.93 t·day^{-1}), followed by fish (722.83 t·day^{-1}), meat (889.53 t·day^{-1}) and grains (146.20 t·day^{-1}).

The food processing establishments are located in metropolitan region of Rio de Janeiro, comprising Niterói, São Gonçalo and Duque de Caxias municipalities. In

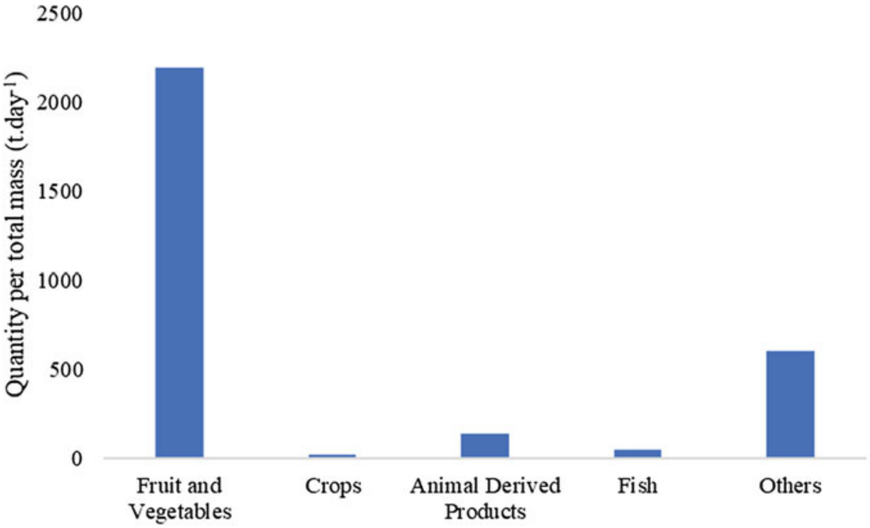

Fig. 4 Total of commercialized food, per type, in CEASA

case of fish processing, a total of 126.20 t·day^{-1} is commercialized in fresh mode and 26.4 t·day^{-1} as canned fish.

At the wholesale market stage, the total food commercialized for the retail market in CEASA during the year of 2016 was 1,531,032.70 t·year^{-1}. The quantity commercialized per day and per kind of food is indicated in Fig. 4.

The first step for carbon footprint evaluation of the food supply chain of the city of Rio de Janeiro is the identification of potential activities which generates GHG emissions. These are the ones who burn materials with carbon compounds, consume derived fossil fuels and nitrogen-based products, generate residues with carbon compounds, manipulates natural ecosystems and raise living animals which produces methane. According to FAO [18], there was more than 290 million of animals in Brazil in 2017, such as cattle, swine and horses, which are responsible for enteric fermentation emissions. In addition, 9,229.20 Gg of nitrogen content present in the manure left in the pasture and 5,172.71 Gg of nutrients present in synthetic fertilizers, and both releases N_2O and CO_2 to the atmosphere annually. Figure 5 presents the total of these Brazilian emissions, per each activity, which was estimated for 2017.

Therefore, Brazil presents a total of 459,159.74 Gg CO_2e·year^{-1} emissions from the agriculture sector, with the enteric fermentation and manure left in pasture being the more carbon-intensive activities, responsible for 58% and 23% of the total emissions in 2017, respectively.

In case of Rio de Janeiro, the state is responsible for 2,386.43 Gg CO_2e·year^{-1} of enteric fermentation activity, considering just the production of 441,131.88 t·year^{-1} of cow milk and 79,527.00 t·year^{-1} of beef in 2018 [13, 14], which corresponds to a 6,538.16 t CO_2e·day^{-1}.

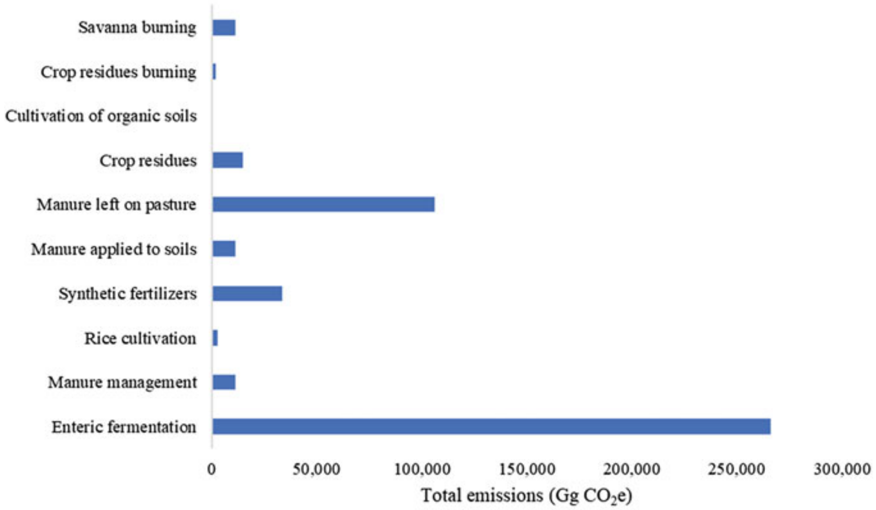

Fig. 5 Brazilian agriculture emissions, per activity, in 2017. *Source* Adapted from FAO [18]

Table 3 Food waste generated in the City of Rio de Janeiro

Establishments	Food waste generated (t·day^{-1})
Supermarkets	13.28
Street fairs	298.53
Wholesaler CADEG	12.99
Wholesaler CEASA	120.27

As stated in the methodology section, presented in Sect. 3, this study aims to quantify GHG emissions associated with the food wastage activities. Table 3 presents the total of food waste quantified per day, for the establishments which are considered for the case study.

From Table 3, it is possible to observe that street fairs are the main responsible establishments for food waste generation in Rio de Janeiro, corresponding to 67% of the total waste generated, followed by CEASA, which is the main wholesaler in the city.

The food loss generated by wholesalers and the food waste generated by the retailers are collected and transported for the transfer stations and, then, are transferred to the municipal landfill of Rio de Janeiro. This is the current scenario where the activities responsible for the direct GHG emissions were identified and the emissions were calculated. On the other hand, if a selective collection is implemented and the food waste could be collected and transported to an anaerobic digestion treatment unit, the food waste will be used as a resource for biogas and biosolid production. This is the alternative scenario proposed in this study, with the SSAD facility in Eco Parque-Caju, Rio de Janeiro, which is considered as the main receptor of the food waste generated. Table 4 indicates the GHG estimation for both current and alternative scenarios, based on daily food waste generation. Also, there is indicated the GHG mitigation by showing the difference of the alternative scenario in comparison to the current scenario applied.

From Table 4, it could be inferred that if the SSAD is adopted and incorporated into the food waste management, as the main destination, the total GHG emission will be a reduction of 90% of GHG emission, which corresponds to 124.09 t CO_2e avoided emissions. Figure 6 illustrates these GHG emissions, per activity.

From Fig. 6, landfilling is illustrated as the main contributor of GHG emissions, with 89.6% of the participation on the total of emission in current scenario. In contrast, the alternative scenario shows more contribution of the other activities, with 57.8% for the collection and transport and 39.9% for the SSAD treatment.

On the other hand, if the GHG emission quantification is done for one year of food waste management, the landfilling practice will produce a total of 1.10 Gg CH_4, which corresponds to 45,315.41 t CO_2e, considering the amount of landfill gas recovered. In contrast, if the SSAD treatment is considered, a total of 2,099.65 t CO_2e will be emitted, just considering any leakage from the biodigesters and the incomplete combustion of on-site CHP equipment. Finally, one year of this alternative scenario promotes the avoidance of 45,291.33 t CO_2e emissions.

Finally, a total of 445.06 t·day^{-1} of food waste, which is used as a feedstock for the AD process, will produce 181,586.32 kg of biosolid for agricultural soils amendment and 38,549.26 m^3 of biogas to be recovery as energy or biofuel. Thus, the circular economy can be implemented and 2.4, 12.3 and 12.5 SDG of Agenda 2030 [40] is achieved, together with the European Directive (1999/31/EC) and Brazilian national policy for solid waste [4], which defines less organic waste masses disposed in landfills.

Table 4 GHG emissions for current and alternative scenarios

Activities	GHG emissions (t CO_2e·day^{-1})		GHG emissions mitigation (t CO_2e·day^{-1})
	Current Scenario	Alternative Scenario	
Collection and transport	8.29	8.33	0.04
Transfer station	4.19	0.00	−4.19
SSAD treatment	0.00	5.75	5.75
Transfer	1.88	0.34	−1.54
Landfilling	124.15	0.00	−124.15
Total	**138.51**	**14.43**	**−124.09**

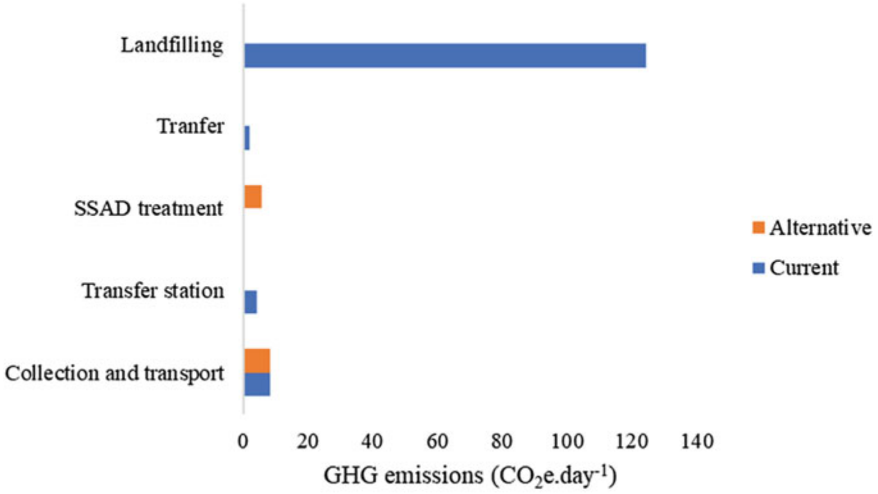

Fig. 6 GHG emissions of current and alternative scenario, per activity

6 Conclusions

The carbon footprint analysis allows the identification of carbon-intensive activities for food supply chain and food waste management networks, which can be a useful tool for decision makers. From the evaluation performed in this chapter, it is highlighted that the enteric fermentation and manure left in pasture are the main responsible for GHG emissions from the agriculture sector in Brazil, which considers the upstream steps of the food supply chain. On the other hand, the carbon footprint of food waste management indicates the intensive contribution for GHG emissions, with landfilling, followed by the collection and transportation practices.

The food waste management evaluation of the case study indicates, for the current scenario, 12,48 t $CO_2e{\cdot}day^{-1}$ from food waste collection and transfer and 124,15 t $CO_2e{\cdot}day^{-1}$ from landfill disposal. In contrast, the alternative scenario shows an opportunity of 90% of GHG reduction for the food waste management, with incorporation of an anaerobic digestion treatment unit. Finally, with one-year implementation of this alternative scenario is expected to avoid 45,291.33 t CO_2e emissions.

Apart from GHG emission reduction, it is worthy to mention that the alternative scenario promotes the circular economy of food waste, with the possibility of 181,586.32 kg of biosolid and 38,549.26 m^3 of biogas production. These valuable products can be used as a resource for supply wholesalers and retailers activities demands and on agriculture production, which brings the primary production closer to urban consumers.

Future works should also focus on the carbon footprint evaluation of the by-products (biosolids and biogas) recovered. For this, it is necessary to estimate the GHG emissions from the incorporation of biosolids in the agriculture use and from the biogas usages as biofuel or to produce energy. In addition, the carbon footprint of the food supply chain steps, such as the food processing and distributed, can also be calculated for the case study. Finally, the carbon footprint analysis of food waste collection and transport can be more accurate if the collection routes are individually evaluated.

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Carbon Footprint of Karnataka: Accounting of Sources and Sinks

T. V. Ramachandra and Setturu Bharath

Abstract Higher greenhouse gas (GHG) footprint with the burgeoning anthropogenic activities has altered the energy cycle contributing to the changes in the climate with the global warming. Imbalances are evident with the increasing levels of carbon dioxide (CO_2) concentrations in the atmosphere. The increased loads of Green House Gas (GHG) emission due to a higher release of carbon content are causing loss of ecosystem services further resulting in climate changes. The forests ecosystems account for ~82% of the continental biomass, a source for higher terrestrial carbon sequestration, playing a vital role in maintaining the carbon cycle and provision of various goods and services, which play a primary role in human's socioeconomic development. The various initiatives and concerns across the globe are rising to account for the carbon emissions and finding the potential measures for regulation. The carbon dynamics in the Karnataka state has been investigated considering the present status of ecosystems, quantification of sector-wise emissions, and projected likely change in sequestration by modeling land-use changes. Karnataka state now has 15% of the geographical area under forest compared with 21% in 1985. The total above and below ground biomass from forests of Karnataka was 782.1 (Tera Gram) in 1985 and reduced to 519.36 Tg by 2019 due to the largescale land-use changes leading to deforestation and land degradation. The loss of 168 Tg carbon sequestration potential confirms the extent of anthropogenic pressure on the state's forest. Carbon sequestered is about 16.1 Tg/year, whereas total emission is around 150.65 Tg. The various sources of carbon emissions were accounted for covering livestock, agriculture to industries for the year 2019 as 150.65Tg, which accounts 5% of India's total emission. Around 11% of the emission has been captured by the forests of Karnataka. The sequestered carbon accounts to INR 34 billion ($0.5

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billion) considering INR 2142 ($30) per tonne for carbon trading, which highlights the scope for higher carbon credits with reforestation of degraded landscapes.

Keywords Carbon sequestration · Emission · Biomass · Footprint · Carbon ratio

1 Introduction

Carbon constitutes the fundamental element in the earth system including the food chain of biota and exists in different forms and reservoirs, which are distributed and continually exchanged among the atmosphere, biosphere, lithosphere, and hydrosphere. Autotrophic organisms uptake carbon dioxide (CO_2) during photosynthesis transforming the energy from the sun into a chemical carbohydrate molecule, converting carbon in the atmosphere to fuel and structural materials for living organisms. Rampant deforestation and fossil fuel burning have been adding to the global carbon dynamics with the transformation of inactive carbon. The activities include burning of fossil fuel (transportation, power generation), industry, agriculture, polluting streams as well as water bodies and unplanned urbanization. Postindustrialization era witnessed an increase in GHG footprint, which constitutes 72% of CO_2. The escalation in human-induced greenhouse gas (GHG) emissions has been witnessed as 400 ppm (parts per million) from 280 ppm CO_2 emissions as compared with preindustrial era, which has contributed to the global warming [5] with changes in the climate, which affected people's livelihood with the erosion of key ecosystem services including ecosystem productivity, water holding capacity, etc.

Forest ecosystems are the large repositories of terrestrial carbon and play a crucial role in the carbon cycle (C-cycle) through sequestration of atmospheric carbon in the above ground biomass (AGB), below ground biomass (BGB), and soil organic carbon (SOC). Forest and soil ecosystems' role in maintaining the carbon balance is evident from the uptake of 30% (2 Pg (petagrams) of the annual anthropogenic CO_2 emissions. The forests storing large quantities of carbon per unit area packed down through photosynthesis, which gets released with the mismanagement of fragile ecosystems due to unplanned developmental activities with anthropogenic pressures [52]. The annual carbon sequestration by the world's forests has been estimated as 2.4 Gigaton C [34]. Soil stores about two to three times more carbon in organic form apart from forest woody biomass [56]. Carbon stored in soils as soil organic carbon (SOC) and the studies focusing on soil's potential in sequestering carbon is scanty and received relatively limited attention from the policy community, compared with carbon storage in the above ground wood biomass [3, 24, 56]. SOC constitutes the largest terrestrial carbon pool with an estimate of 700–3000 PgC (1 PgC = $1*10^{15}$gC) across the globe [6]. SOC content in the soils varies based on climate, moisture, physiography, soil type, elevation, terrestrial vegetation type, density, and extent. However, inappropriate land-use changes with mismanagement, soil becomes a source of greenhouse gas emissions (CO_2, CH_4). This necessitates prudent land management in agricultural practices, restoration of eroded and degraded forest soils to improve soil carbon pool [25]. The C pool in the topsoil is about 2011 PgC [33] accounting to 4.1 times of the biotic pool, and three times of the carbon in the atmosphere. Soil Organic Carbon (SOC) in the top 50 cm soil depth in India is estimated to be about 92.1 tons per ha in littoral swamp and 37.5 tons per hectare in tropical dry deciduous forests [6]. The total SOC in Indian forests accounts to 4.13 PgC (top 50 cm soil depth) and 6.81 PgC (top 1 m), which highlights the need for protection of soil with the appropriate conservation strategies to mitigate greenhouse gas emissions and associated climate changes.

Burning of fossil fuel [30], escalated industrial activities [29], higher deforestation [4], and land degradation [41] highlight the extent of anthropogenic-induced global warming. This unrestrained increase in global atmospheric carbon since the dawn of industrial revolution and implications changes in the climate on water and food security has driven the attention of policy-makers across the globe to focus on the earth's carbon stocks and flows. Large-scale land-use land cover changes (LULC) altering the integrity of forests, soil and aquatic ecosystems with the associated emissions have been contributing toward higher greenhouse gas (GHG) footprint. LULC changes have not only eroded the sequestration capability directly but also disturbed the amount of vegetation residues (organic matter) returned to the soil [36, 49]. LULC changes have been posing a greater threat by altering their potential of sequestration, escalating vegetation die-off, and increasing instances of wildfire [13] and have contributed to about one-third of all anthropogenic carbon [19]. LULC change-induced deforestation resulting in 90% of net carbon emission across the globe and acting as a source of 20% annual greenhouse gas emissions into the atmosphere [33]. This has prioritized the need for understanding of LULC changes with the associated decline of biomass and carbon storage for framing international policy strategies to reduce greenhouse gas emissions by reducing the abrupt LULC changes. LULC changes and their impacts vary across the regions, which necessitates the regional-specific management [42] in contrast to the global policy and regulation. Agriculture, energy production, industrial activities, waste mismanagement, and transportation are the major carbon-emitting sectors to be accounted for carbon budgeting as mismanagement in these sectors have contributed to a higher quantum of greenhouse gas emissions [1, 2, 58, 63].

The systematic quantification of carbon stock with an assessment of GHG emissions from various sectors would aid in framing the land-use policies and curb the irrational carbon emission from abrupt LULC changes. The global CO_2 emission is quantified as 36,153 million tons, with countries such as China (27%), USA (15%), European Union (10%), and India (7%) accounts 58% of the total emissions [26]. The top 15 countries contribute 26,125 million tons and the rest of the world as 10,028 million tons. The top 15 countries contribute 72% of CO_2 emissions and 28% by the rest (of 180 countries). China alone accounts to produce on its own 28% of CO_2 emissions (9.8 billion tons), 18.8% of global methane emissions (1.7 billion tons CO_2e), and 18.4% of N_2O emissions (545 million tons CO_2e). Large-scale LULC changes leading to deforestation account for 8% of the global carbon emissions (4.9 billion tons per year in the tropical forests). This has been responsible for dynamics in carbon stocks with the lowered capability of carbon sequestration, which has prompted to assess the extent and role of drivers of the carbon emissions to evolve strategies to mitigate changes in the climate. Advancements in Geoinformatics (GIS technologies) and availability of the multi resolution temporal remote sensing data with field data have aided in the land-use land cover mapping, quantification of above ground biomass (AGB), below ground biomass (BGB), and soil carbon. The remote sensing with continuous data support has been useful in the quantification of carbon footprint through measurement of carbon stock and emissions, which vary with the climate, land-use practices, and changes in the land cover and land uses [7, 40]. The insights of carbon dynamics through quantification of carbon footprint and the extent of carbon removal by carbon sinks would help in evolving strategies and frame appropriate policies to mitigate carbon footprint and implement location-specific conservation measures.

Afforestation with the location-specific endemic species of vegetation, arresting deforestation process through the improved regulatory mechanisms, transition to the energy-efficient devices, and environmentally sound technologies are some of the potential approaches for sequestering carbon and mitigate carbon emissions. Plants (trees, grasses, herbs) take up atmospheric carbon dioxide during photosynthesis and stored as carbon in biomass (trunks, branches, foliage, roots) and soils. Storing carbon in forests or through plantations in the form of standing biomass constitutes a potential carbon capture and storage (CCS) option [32]. The global potential of carbon sequestration through plants was estimated as 5–15 Gt C/year, which depends on the land-use practices, climate, etc. [23]. REDD and REDD + initiative (Reducing Emission from Deforestation and Degradation) developed by Parties to the United Nations Framework Convention on Climate Change (UNFCCC) is an efficient strategy to promote conservation while reducing greenhouse gas emissions due to deforestation and forest degradations (accounting to 11% of global carbon emissions). Mitigation of impacts of the changes in climate and stabilizing global average temperatures within two degrees Celsius entails reducing emissions from the forest sector, in addition to other sector mitigation actions. REDD + creates a financial value for the carbon stored in forests by providing financial incentives to the developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development through increasing forest cover, lessening nationwide deforestation rates, carbon emissions, and reducing degradation of various geographical regions [57]. The carbon credit payment scheme as per the Kyoto Protocol obligations is another initiative to curb the carbon and carbon sequestration through effective management. The scheme allocated credits according to the actual amount of carbon sequestered by the trees as modest land based ($77.91 per hectare per year) and tree based ($0.2 per m^3 per year) to minimize the abandonment or degradation of forests [18]. These international initiatives toward mitigation of carbon dioxide emissions through improved forestry activities necessitate the understanding of spatial and temporal carbon dynamics. Objectives of the current research are (i) understanding spatial patterns of land-use dynamics in Karnataka State, India; (ii) quantification of the carbon emissions; (iii) estimation of the carbon sequestration potential of forests plants and soil; (iv) assessment of the impact of LULC changes on carbon sequestration potential; (v) likely scenario of carbon dynamics with the current trends of changes and also likely changes due to the policy of large scale developmental projects; and (vi) suggestions towards reducing deforestation and land degradation.

2 Materials and Method

2.1 Study Area

Karnataka covers an area of 191,976 km^2 (19 million hectares) with a share of 6% in the national GDP is located in the southern part of India, sharing borders with Maharashtra and Goa; Andhra Pradesh and Telangana to the east; Tamil Nadu and Kerala to the south, while the Arabian Sea forms the western boundary (Fig. 1). The population of the state was 611,30,704 inhabitants (as per 2011 census) with a density of 319 per km^2. The state is known for its diverse culture, scenic beauty, languages, economic, and social profiles. Karnataka state is divided into four revenue divisions, 49 subdivisions, 30 districts, 175 taluks, and 745 hoblies/revenue circles for decentralized administration. The Western Ghats, one of the 36 global biodiversity hotspots (https://www.conservation.org) covers 60% of the state's forest cover in the western portion with diverse flora and fauna. The region has diverse forest cover types such

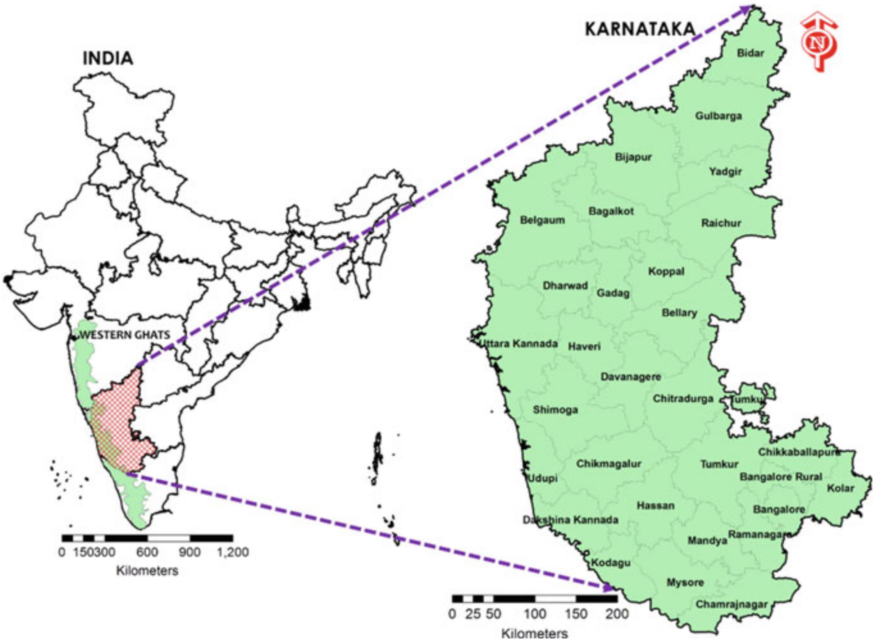


Fig. 1 Study Area—Karnataka State, India. *Source* Author

as evergreen, moist as well as dry deciduous, scrub, thorny, sholas, grasslands, and mangroves in the estuarine areas. The state harbors 4500 species of flowering plants, 508 species of birds, 150 varieties of mammals, 156 reptile species, amphibians of 156 species, 405 fish species, and 330 butterflies. Soils of the state are fertile by two major river systems (Krishna, Cauvery) and its tributaries. The state has a protected area network of five national parks (2431.3 km^2) and 21 wildlife sanctuaries (3887.83 km^2), covering nearly 16% of forest area. Agriculture and horticulture sectors are the backbone of the state's economy. The state is the prime destination for IT and BT technologies with knowledge, innovation, research, and development centers. It has a gross domestic product (GDP) of ₹15.10 lakh crore (US$220 billion) as fourth largest in India, growing at a healthy 7% per year with a per capita GDP of ₹207,000 (US$3,000).

3 Method

The protocol adopted to assess the carbon dynamics in Karnataka is presented in Fig. 2. The research involved (i) assessment of land-use dynamics through spatial data acquired using spaceborne sensors at regular intervals; (ii) field data collection to classify remote sensing data, (iii) quantification of AGB through field measurements of girth and height and sampling of the locations through transect based quadrat; (iv) quantification of carbon across various forest types and soil; (v) data mining pertaining to carbon emissions, sequestrations in forests and soils through published literature; (vi) visualization of likely changes in carbon dynamics (a) with the current rate of deforestation and degradation; (b) interventions with the afforestation; (c) implementation of the proposed development projects. This was implemented in three phases. Phase 1 focused on the land-use analyses, Phase 2 estimates the carbon sinks as well as its variation over time; quantified the emissions across each sector followed by carbon budgeting, and likely changes in carbon dynamics are predicted in Phase 3.

Land-use dynamics—Spatial patterns of land-use dynamics assessment using temporal remote sensing data: The remote sensing data of Landsat series for 1985, 2005, 2019 (downloaded from the public domain https://landsat.org) were analyzed through efficient supervised classifier based on GMLC (Gaussian Maximum Likelihood Classifier) algorithm using free and opensource GRASS GIS (Geographical Analysis Support System—https://wgbis.ces.iisc.ernet.in/grass/). The field investigation has been carried out for collecting training data, which was used to classify the remote sensing data of 2019 coinciding with the field data collection period. The earlier time remote sensing data were classified using collateral data compiled from various sources such as Karnataka Forest Department reports (https://aranya.gov.in), vegetation map of South India of 1:250,000, the French Institute of India (https://www.ifpindia.org). The process of remote sensing data classification involved (i) preparation of false-color composite (FCC) using five bands (R, G, and NIR) of LANDSAT satellite data, which assisted in the selection of training sites through the

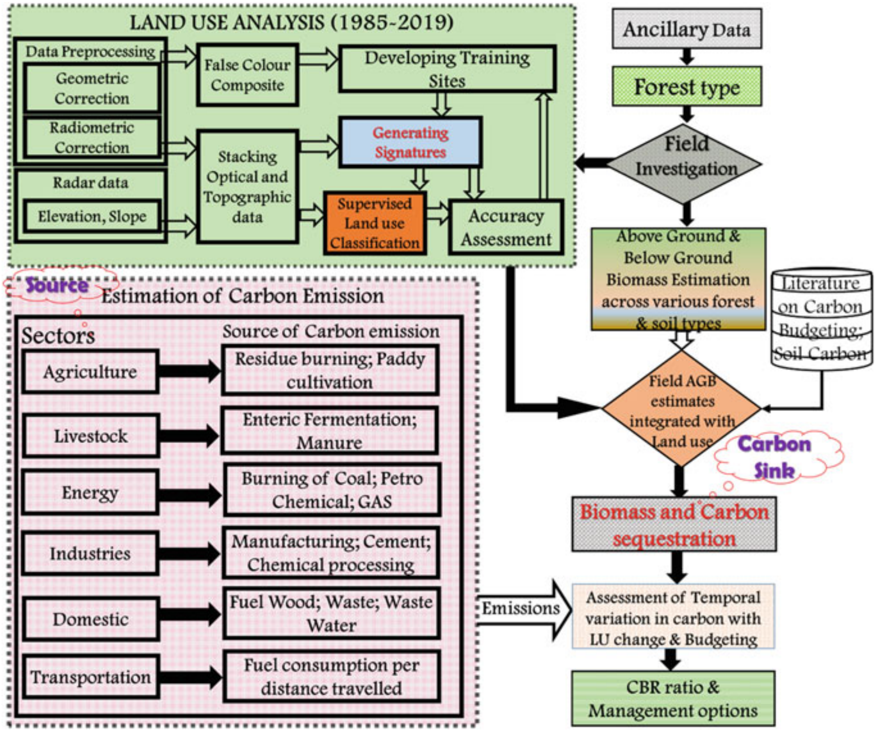


Fig. 2 Method adopted for carbon budgeting for Karnataka. *Source* Author

identification of heterogeneous patches corresponding to diverse landscape elements, (ii) attribute data collected in the field corresponding to these training polygons using precalibrated GPS (Global positioning system) and virtual data (Google Earth—https://earth.google.com, Bhuvan https://bhuvan.nrsc.gov.in), (iii) classification of RS data for eight different land-use categories through GMLC algorithm using training data, and (iv) accuracy assessment of classified remote sensing information was done through error matrix (contingency matrix) and K^{Λ} statistics (Kappa). The training data compiled from field (60%) have been used for classification, while the balance is used for accuracy assessment and validation [28].

3.1 Estimation of Spatiotemporal Carbon Sequestration Potential

The carbon sequestration potential of forest ecosystems, plantations, and agriculture areas was assessed based on (i) field estimations carried out in the forests across Karnataka state using transect cum quadrat based sampling techniques and (ii) published literature based on the rigorous distinctive biomass experiments. The study region (Karnataka State) was divided into 2597 grids of $5' \times 5'$ (or 9 km × 9 km) grids corresponding to $5' \times 5'$ grids of 1:50,000 topographic maps of the Survey of India. Select grids corresponding to agroclimatic zones were chosen for biomass and carbon estimation through field investigations. The basal area, height, vegetation type (evergreen, deciduous, semievergreen, moist deciduous, scrub forests), diversity, biomass, carbon, etc., were estimated aiding field data. The comprehensive field evaluations were done across various forest cover types with about 424 transects in Uttara Kannada, Dharwad, Shimoga, Udupi, Chikmagalur, Dakshina Kannada, and Kodagu districts. The number of quadrats per transects varied between 3 and 5 depending on the occurrence of species in the sampling locality. The biomass was estimated using GBH or DBH (girth/diameter at breast height) for the trees >30 cm. The transect data and standard literature data were used for biomass quantification. The biomass, annual increment in biomass of various forest types, sequestered carbon, productivity have been computed using field data integrating with the information compiled from literature, which are listed in Tables 1 and 2. The probable relationship of biomass with the vegetation cover has been evaluated through multivariate regression analysis across coastal, Sahyadri, plain regions of Karnataka. The carbon for above ground vegetation is computed as 50% of AGB value. The carbon is deposited in the soil as soil organic matter in both organic (SOC) and inorganic forms. SOC is calculated based on the field estimations in top 30 cm soil for different forests (Table 3) and mean soil carbon reported in the literature [31, 55, 40].

3.2 *Quantification of Carbon Emission from Various Sectors*

Data pertaining to emission for sectors such as agriculture, livestock, industry, energy, transportation, etc., were compiled from published literature.

3.2.1 Agriculture

Agricultural residue burning is practiced in some taluks across Karnataka. Emissions due to crop residue burning were computed as per the guidelines of IPCC and literature [11, 61] based on the area of crop grown to the standard crop residue ratio. The total emission is estimated by summing of CO_2; methane (CH_4) and Carbon monoxide (CO) (its equivalent CO_2) values [17, 33]. The emission from agriculture residue (AR_e) burning is estimated as,

$$AR_e = \sum_{i=1}^{3} \sum \left[\text{Cropresidueratio} \times \text{emissioncoefficient} \right] \quad (1)$$

Table 1 Forest type-wise quantification of biomass and sequestered carbon

Index	Forest type	Equation	Quantification
Biomass (T/Ha)	Evergreen	(Forestcover) × 485.67	Above ground biomass content
	Deciduous	(Forestcover) × 258.12	
	Scrub	(Forestcover) × 74.25	
	Plantations	(Extent) × 45.25	
Carbon stored (T/Ha)	All	(Estimatedbiomass) × 0.5	Sequestered carbon
Annual Increment in Biomass (T/Ha)	Evergreen	(Forestcover) × 10.48	Incremental growth in biomass [8, 10, 35, 40, 46, 48]
	Deciduous	(Forestcover) × 13.82	
	Scrub	(Forestcover) × 5.4	
	Plantations	(Extent) × 1.4	
Annual increment in Carbon (T/Ha)	All	(AnnualIncrementinBiomass) × 0.5	Incremental growth in carbon storage
Net annual Biomass productivity (T/Ha)	Evergreen	(Forestcover) × 3.6	Used to compute the annual availability of woody biomass in the region
	Deciduous	(Forestcover) × 3.9	
	Scrub	(Forestcover) × 0.5	
Carbon sequestration of soil (T/Ha)	Evergreen	(Forestcover) × 132.8	Carbon stored in soil [7, 38, 55]
	Deciduous	(Forestcover) × 58	
	Scrub	(Forestcover) × 44	
	Agriculture	(Extent) × 2.43	
	Plantations	(Extent) × 55	
Annual Increment of soil carbon (T/Ha)	All	(Cover) × 2.5	Annual increment of carbon stored in the soil

Table 2 Above ground biomass for different forest types and plantations

Sno	Forest cover type	Standing Biomass (T/ha)	Source
1	Dense Evergreen to Semi evergreen	486–834	Field-based transect cum quadrat method; [20, 37, 38, 40, 43, 46–48, 53]
2	Low evergreen	226	
3	Dense Deciduous	258	
4	Degraded Deciduous	130	
5	Savanna Woodlands	75–90	
6	Thorn degraded	40	
7	Littoral and swamp	215	
8	Plantations	45–126	

Table 3 Soil carbon storage in different forest types and agriculture filed

Sno	Forest cover type free and opensource	Mean SOC in top 30 cm (t/ha)	Source
1	Tropical Wet Evergreen Forest	132.8	[20, 22, 40, 54, 55, 62]
2	Tropical Semi Evergreen Forest	171.75	
3	Tropical Moist Deciduous Forest	57.14	
4	Littoral and Swampy Forest	34.9	
5	Tropical Dry Deciduous Forest	58	
6	Tropical Thorn Forest	44	
7	Tropical Dry Evergreen Forest	33	
8	Agriculture Fields	4	
9	Plantations	55”	

3.2.2 Livestock

Livestock plays an important role in the agroecosystem, apart from the critical energy input to the croplands, also provides economic support to the farmers in terms of milk, manure, soil nutrient enrichment, etc. Livestock also produces CH_4 emissions from enteric fermentation and CH_4 and N_2O (nitrous oxide) emissions are from manure management systems. The agriculture sector accounts for approximately 20 and 35% of global GHG emissions [11]. The grid-wise livestock density has been estimated and associated emission was quantified under enteric fermentation as well as manure management [9, 21, 60]. Livestock population (Census 2012) data were obtained from the State Veterinary Department, Government of Karnataka, and respective emission factors are listed in Table 4. CH_4 emissions (kg CH_4/animal/year) due to the enteric fermentation are computed as,

Table 4 Emission factors associated with livestock

Livestock variety		Emission factor(Kg/Head/Yr)	
		Enteric fermentation	Manure management
Cattle	Indigenous	34.05	3
	Crossbred	29.42	3.46
Buffalo		54.28	3.36
Sheep		3.67	0.16
Goat		4.99	0.17
Others		8.64	4

$$\mathrm{CH_4EntericFermentation} = \sum_{\mathrm{I}} (\mathrm{EF_I} \times \mathrm{N_I})/10^6 \tag{2}$$

where, $\mathrm{EF_I}$ is an emission factor for the individual livestock category, $\mathrm{N_I}$ is the number of animals of livestock for category I. The emission from manure depends on volatile solids or ruminants, their productivity, and manure handling system [51]. Methane emission due to manure management is estimated as,

$$\mathrm{CH_4Manuremanagement} = \sum_{\mathrm{I}} (\mathrm{EF_I} \times \mathrm{N_I})/10^6 \tag{3}$$

where $\mathrm{EF_I}$ is an emission factor for each livestock category; $\mathrm{N_I}$ is the number of livestock for category I in the region. Further, CO_2 equivalent values have been estimated across the grids for the fermentation and manure emissions.

Paddy cultivation is another major activity across the globe, contributing for 20% methane emission [64]. Paddy is grown in all taluks of Karnataka state and emission from paddy *(Oryza sativa)* is estimated across the grids as,

$$\mathrm{CH_4Paddy} = [EF \times T \times A] \tag{4}$$

where EF is the daily emission factor (kg CH_4/Ha/Day), T is the cultivation period, A is the harvested area (in two seasons-*Kharif; Rabi*).

3.2.3 Domestic

The fuelwood consumption is causing deforestation and an increase in C02 emission. The Per Capita Fuel Consumption (PCFC) was analyzed to account fuelwood consumption pattern across the agroclimatic zones of state and determined the carbon emissions (EFC) as,

$$EFWC = [NH \times PCFC \times EF] \tag{4}$$

where EFWC is carbon emission from fuelwood consumption in rural households, PCFC is per capita fuel consumption (which was computed as ration of fuelwood consumed in kgs/day and number of adults in a household), EF is emission factor.

The waste generated per household level is also contributing to the CH_4 emissions due to the disorganized management of waste across the state. The waste generated across individual households of Karnataka at the grid level has been estimated considering 0.35 g per person per day [45]. The average of four people per household was considered for a total of 2,281,419 households. The emission from waste per year is calculated as,

$$EWC = [0.35 \times NH \times 365] \tag{5}$$

where EWC is carbon emission from waste generated, NH is the number of households.

Nitrous oxide (N_2O) emissions can occur as both direct and indirect emissions, apart from CH_4 through domestic wastewater, which has significant carbon loading [16]. The emission from wastewater generated from the individual households is estimated by considering average water consumption per person per day as 135 L [39, 45, 59].

3.2.4 Industries

Karnataka state is endowed with rich mineral resources as well as a large pool of human resources. The state has public sector units and also gives impetus simultaneously to private sector growth, which prompted to establish many industries. The state has major manufacturing industries due to progressive industrial policies. The good Institutional networks such as Search Results Karnataka Industrial Area Development Board-KIADB (en.kiadb.in), Karnataka State Small Industries Development Corporation Ltd-KSSIDC (kssidc.co.in), Karnataka State Small Industries Development Corporation Ltd-KSSIMC, Technical Consultancy Services Organisation of Karnataka-TECSOK (tecsok.com), Federation of Karnataka Chambers of Commerce and Industry-FKCCI (fkcci.org), and Industries and Commerce Department (kum.karnatka.gov.in) were set up to provide various assistance for industrial development in the state. The major manufacturing industries such as cement, steel, iron ore processing, petrochemical, sugar, paper, and paper board, etc., were considered [12] and associated emissions [51] were estimated based on the standard protocol (Annexure-I).

3.2.5 Energy

The energy sector is considered to account emissions from thermal (burning of coal) and diesel power generation. The state has an installed power generation capacity of 28,789.99 MW of which, central utilities contribute 4123 MW, private utilities contribute 13,259.71 MW and 11,407.28 MW under state utilities. The thermal power contributes 9,560.82 MW, 698.00 MW by nuclear, and 8,431.34 MW by renewable energy sources for the total installed power generation capacity. The various thermal and diesel power generating units were mapped across the state and emissions associated were estimated (Annexure-II).

3.2.6 Transportation

Karnataka stands fifth as per registered motorized vehicles and contributing 7% of registered vehicles of India. Bengaluru has a large quantum of vehicles after Delhi with higher vehicle registrations. The quantum of registered vehicles in the state has been gradually increasing at an average growth rate of 10% per annum and the decadal growth rate of vehicles at 138%. The two-wheelers account for 70% of the registered vehicles across the six divisions (Table 5). The emission from each type of vehicle was evaluated by computing annual average distance traveled (AADT) [15, 39, 44]. The total emission from the transportation sector has been quantified as,

$$Et = \left[\sum \left(V_i \times AADT_i \times EF_{i,jkm}\right)\right] \tag{6}$$

where, E_t is the total emission from the transportation sector, V_i = Number of vehicles per type i, $AADT_i$ is the annual average distance traveled per different vehicle types and $EF_{i,j,km}$ is the vehicle type (i) emission of factors (j), per driven kilometer (Table 6).

3.3 Carbon Ratio (CR)

CR was computed as a ratio of total carbon uptake (from AGB, SOC) to the total emissions across all sectors, which will provide the carbon status across the grids in Karnataka. CR values of "0" and close to 0 represent the regions of higher emission and value greater than 1 represent carbon sequestration is higher in that grids.

$$CR = \left[\frac{\sum (CarbonSequestration)}{\sum (CarbonEmission)}\right] \tag{7}$$

4 Results and Discussion

4.1 Quantifying Spatiotemporal Land-Use Changes

Temporal land-use analyses reveal the decline of forest cover in Karnataka from 1985 to 2019 (Fig. 3). Currently, 15% of the State's geographical area is under forests compared with 21% in 1985. Large-scale developmental activities such as the construction of a series of reservoirs and dams, creation of special economic zones, townships, land conversion for built-up areas have led to the loss of large tracts of forests. The abrupt land-use conversion has resulted in a loss of productive agriculture lands near the cities such as Bengaluru, Mysore, Hubli-Dharwad, Shimoga, etc. The districts such as Kodagu, Uttara Kannada, Bengaluru, Shimoga, Belgaum, Dakshina Kannada, and Chikmagalur have been experiencing a large-scale land cover due to the unplanned developmental activities. Post-1990s, the state witnessed large-scale land-use transitions due to industrialization, urbanization, an increase of horticulture crops, conversion from agriculture to market-based crops (higher economic), etc.

Table 5 Vehicle details of Karnataka

Division (JCT)	Area (km^2)	Two-wheeler	Car	Tractor	Truck	Bus	Taxi	Auto	Other vehicles
Shimoga	38,459.99	1,174,399	74,474	141,372	56,292	22,083	18,538	47,184	24,055
Belgaum	54,488.08	1,343,729	157,265	98,754	57,899	17,952	21,353	51,520	31,274
Kalburgi	44,140.98	1,714,243	262,872	151,226	101,795	24,939	43,036	83,077	54,259
Mysore	27,828.62	2,136,040	166,668	265,345	102,511	44,927	30,955	71,196	40,006
Bangalore Rural	22,333.5	4,186,111	1,188,284	17,439	197,462	88,731	105,421	203,787	71,955
Bangalore Urban	4492.67	1,109,947	96,344	108,718	45,003	14,318	22,230	45,890	18,589
AADT (km)		10,000	15,000	5000	30,000	60,000	30,000	40,000	12,600

Table 6 CO_2, CH_4, and N_2O EF for different type of vehicles

Type of Vehicle	CO_2 EF (g/km)	CH_4 EF (g/km)	N_2O EF (g/km)
Two-wheeler	27.79	0.18	0.002
Car	164.22	0.17	0.005
Taxis	164.22	0.01	0.01
Bus	567.03	0.09	0.03
Auto	64.16	0.18	0.002
Truck	799.95	0.09	0.03
Tractor	515.2	0.09	0.03
Other Vehicles	273.46	0.09	0.03

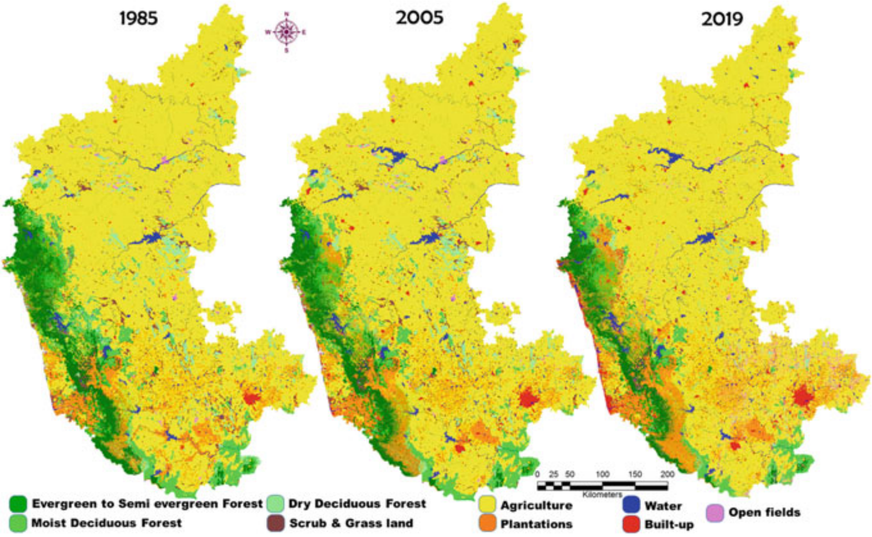


Fig. 3 Spatiotemporal land-use changes in Karnataka. *Source* Author

The forest cover now is confined to major conservation reserves such as protected areas, national parks, wildlife sanctuaries. The built-up cover has increased from 0.47 to 3% from 1985 to 2019 causing an impact on agriculture, forest, and lakes (Fig. 4). This necessitates the sustainable land-use policies to arrest deforestation and abrupt land conversions.

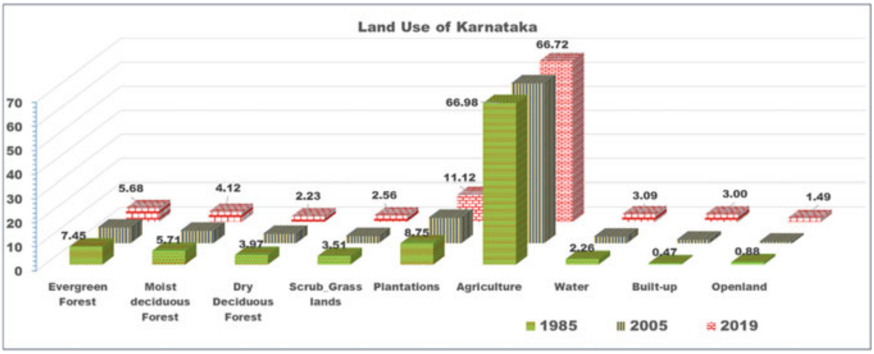


Fig. 4 Land-use dynamics in Karnataka during (1985–2019). *Source* Author

4.2 Carbon Sequestration Potential of Forest Ecosystems in Karnataka

The field data supplemented with data from published literatures were used to compute per hectare biomass across various types of forests in Karnataka. The analyses of the above ground biomass show that the grids in the Western Ghats part of Karnataka have higher AGB > 1000 Gg (Giga gram). The grids of evergreen forested areas represent the greater values of biomass compared with the other forest types. The total AGB of forests is about 1013.7 Tg (Teragram) with stored carbon of 506.8 Tg (in 1985), which is now reduced to 678 Tg and 339 Tg, respectively (2019). The temporal decline of AGB values in the districts of Kodagu, Shimoga, Uttara Kannada, and Dakshina Kannada is due to anthropogenic pressure (Fig. 5). The Mysore Chamrajnagara and Bellary districts also reflect a decline in AGB values during 2005–2019. The districts of Uttara Kannada, Kodagu, Udupi, Chikkamagaluru with relatively higher forest cover have higher carbon sequestration compared to the other parts of the state. The temporal decline in carbon sequestration is due to the deforestation and land degradations due to the sustained anthropogenic pressures (Fig. 6). The annual increment in carbon from forests depicts the grids of Western Ghats has higher increment (>20 Gg) compared with other parts of the state due to less disturbances (Fig. 7). The temporal changes in incremental biomass and carbon highlight the decline of forest cover. The districts such as Shimoga, Mysore, Bellary have lower incremental biomass and carbon values due to deforestation with the rapid land-use changes (Fig. 8). Temporal BGB highlights the decline from 275 Tg (1989) to 180 Tg (2019). The grids consisting of evergreen forests (of Western Ghats) show higher values of >600 Gg SOC, while other regions are with relatively lower values (Fig. 9). The loss of forest cover has degraded the SOC potential and the region is exposed to the sunlight resulting in emissions. The incremental BGB is estimated to understand the increment during 1989–2019, which further confirm of variations (Fig. 10). The districts such as Uttara Kannada, Kodagu, Dakshina Kannada forests

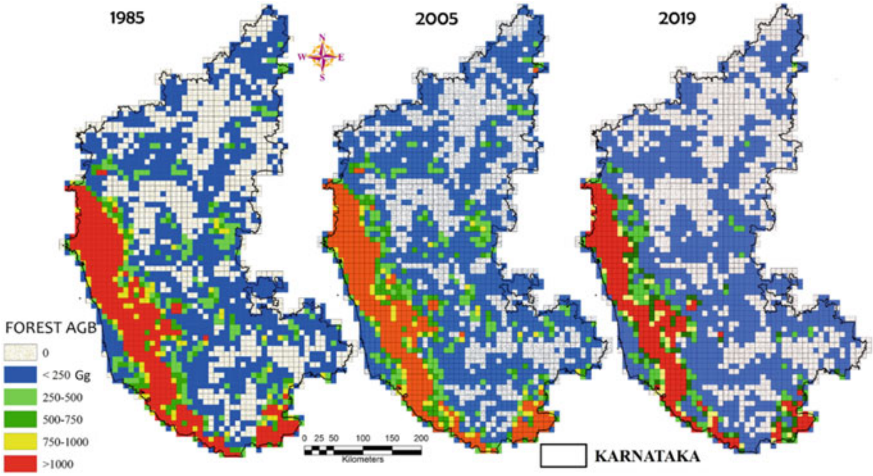


Fig. 5 Temporal AGB in forest areas of Karnataka. *Source* Author

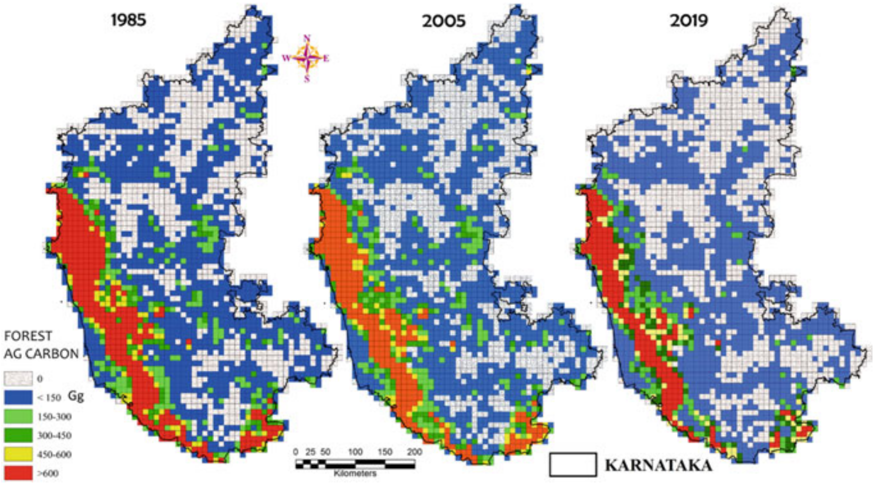


Fig. 6 Temporal variation in carbon sequestration for forest areas of Karnataka. *Source* Author

have grids expressing moderate incremental BGB of greater than 6 Gg compared with other districts across the state.

In order to protect the land under greening initiatives and to sustain market demand for the timber, Karnataka forest department has implemented monoculture plantations in the state. The AGB, BGB, and their carbon values were accounted to understand the role of plantations in carbon sequestration apart from arresting land degradations. The total carbon has been estimated based on the AGB and BGB values as a sum of forest and forest plantations biomass. Figures 11 and 12 show the AGB

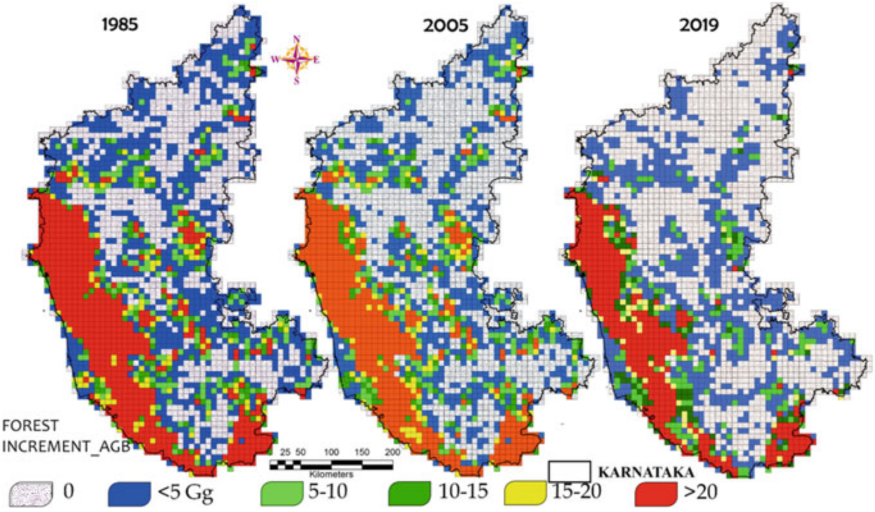


Fig. 7 Annual increment in AGB in forest from 1989 to 2019. *Source* Author

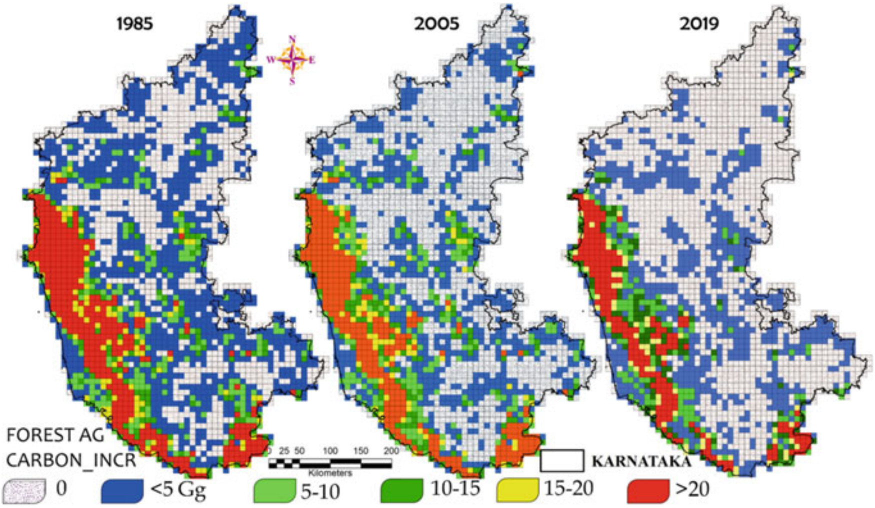


Fig. 8 Annual increment in forest carbon from 1989 to 2019. *Source* Author

for forest and plantations accounted to 1056.90 Tg with carbon sequestration of 528.45 Tg (in 1985), which is now reduced to 732.83 Tg and 366.41Tg, respectively. Figure 13 shows BGB from forest plantation and agriculture areas across the state accounted to 275.43 (1985), which is now reduced to 180.54 Tg. The plantations though not shown any significant contribution of ecosystem services compared with

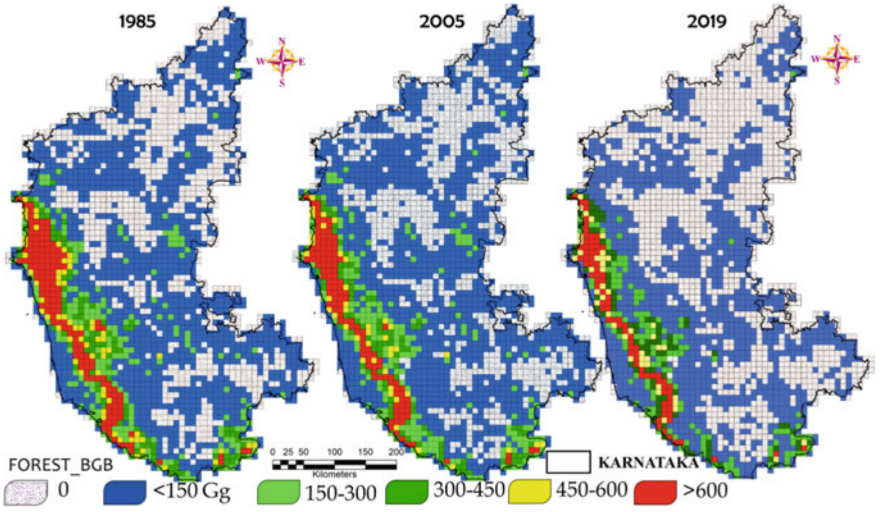


Fig. 9 BGB across the forests of Karnataka from 1989 to 2019. *Source* Author

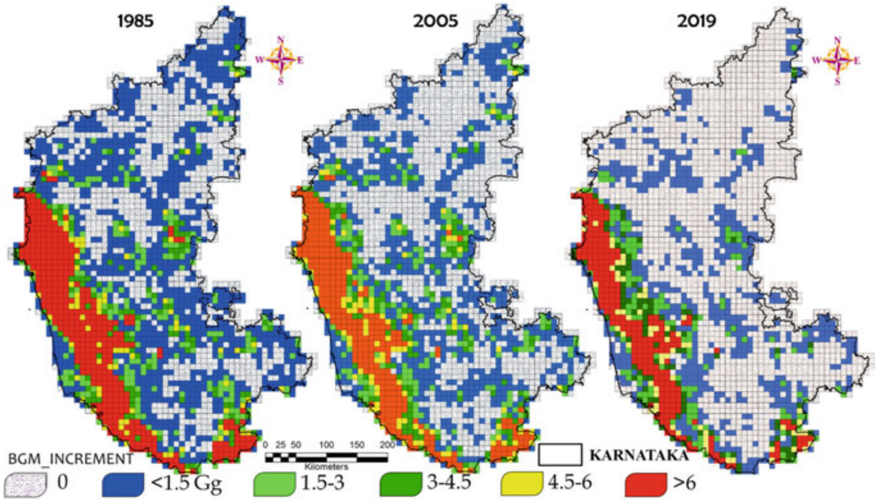


Fig. 10 Incremental BGB values in Forests of Karnataka. *Source* Author

the forest, but supported in sequestration. The Uttara Kannada grids have significant AGB and BGB values.

Total AGB and BGB from forests are about 782.1 Tg (1985), which is reduced to 519.36 Tg (2019) due to LU conversions (Fig. 14). The total carbon sequestration from forest plantation and agriculture areas together is about 1289.1 Tg (1985) and 858.48 Tg (2019) due to changes in LU with the burgeoning anthropogenic pressures.

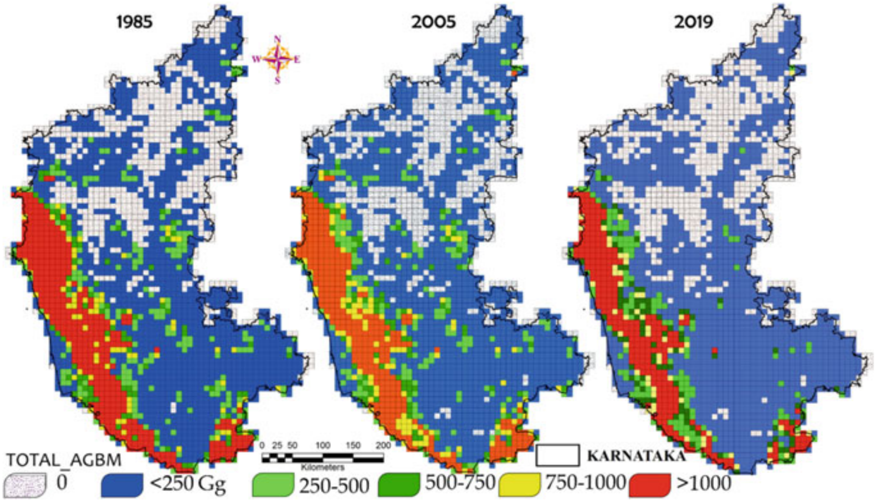


Fig. 11 Total AGB of Karnataka from 1985 to 2019. *Source* Author

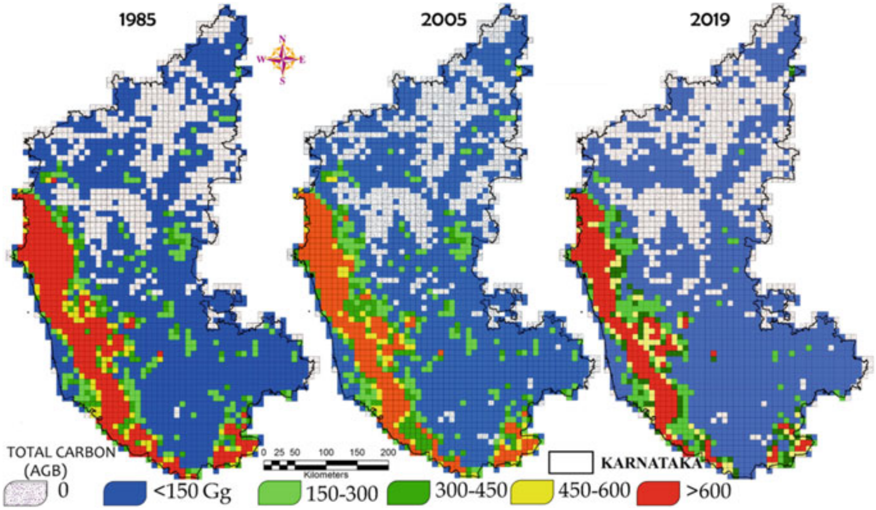


Fig. 12 Total carbon from AGB of Karnataka from 1985 to 2019. *Source* Author

Figure 15 depicts the loss of carbon sequestration of 433.43 Tg during 1985–2019 in the forest, plantation, and agriculture sectors. The loss of 264 Tg carbon sequestration potential during 1985–2019 emphasizes the need for prudent management activities to curb the forest loss and improvement of carbon sequestration (Fig. 16). The grids covered in districts of Bellary, Mysore, Chamarajanagar, Uttara Kannada, Kodagu have witnessed higher transitions in carbon sequestration potential.

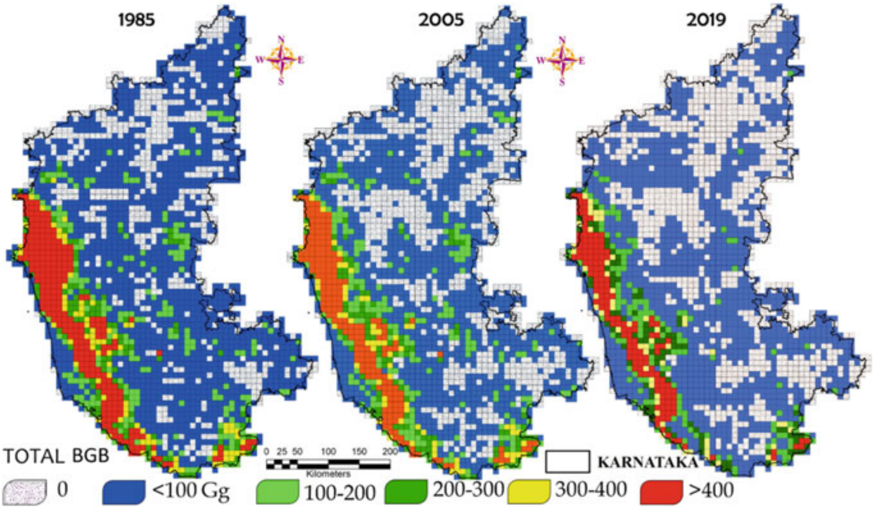


Fig. 13 Total carbon from BGB of Karnataka from 1985 to 2019. *Source* Author

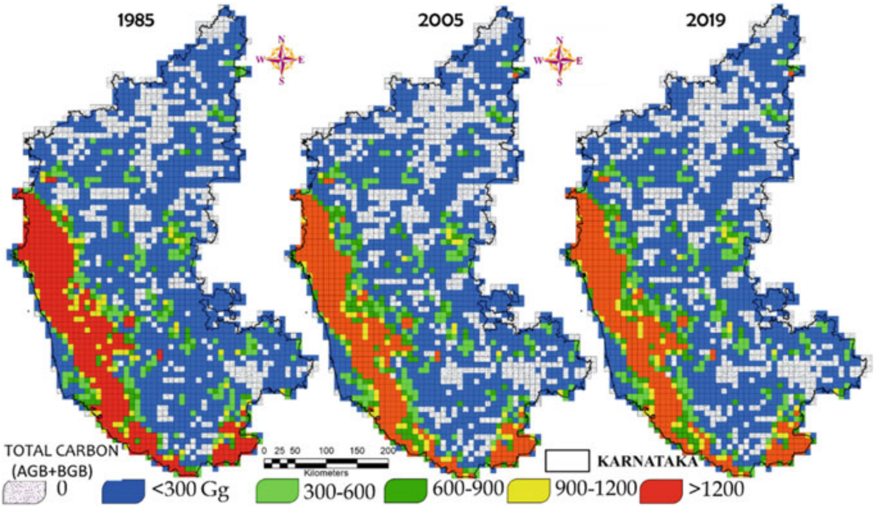


Fig. 14 Total carbon from AGB and BGB of Karnataka from 1985 to 2019. *Source* Author

4.3 Quantification of Carbon Emissions in Karnataka

The carbon emissions from various sectors including livestock, agriculture, and industries for the year 2019 were accounted to be 150.65 Tg. The energy and transportation are a major source of emissions in Karnataka, highlight the necessity of mitigative interventions. Figure 17 highlights major contributions from industrial

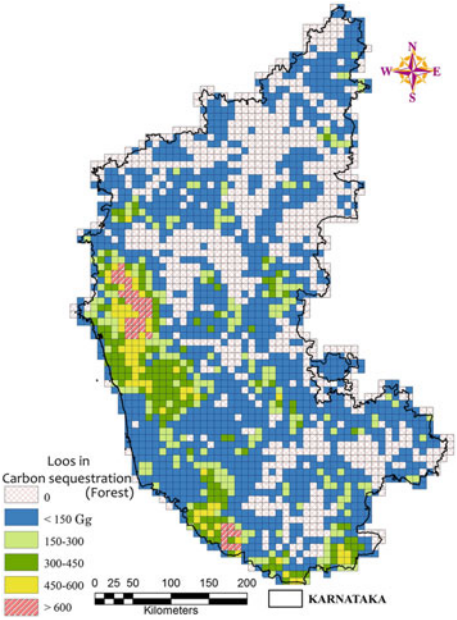


Fig. 15 Loss in carbon sequestration of forests from 1985 to 2019. *Source* Author

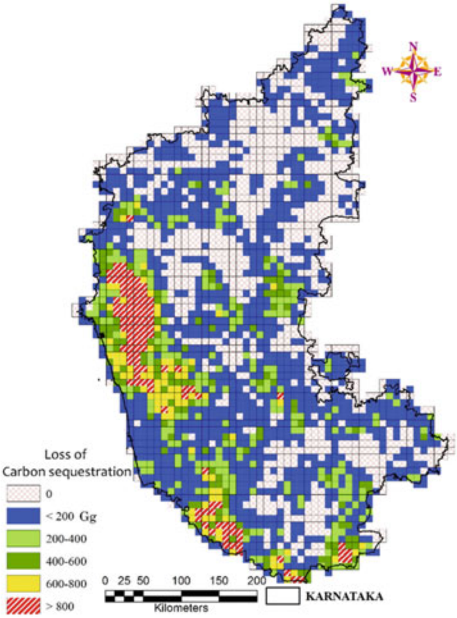


Fig. 16 Loss in carbon sequestration from forests, plantations, agriculture sectors (1985–2019). *Source* Author

Fig. 17 CO_2 emission from various sources in Karnataka. *Source* Author

activities (29%), energy generation (28%), transportation (25%), and paddy cultivation (13%). Large-scale industries having the capacity of greater than 20,000 tons and covering various sectors of cement, petrochemical, steel, paper mills, etc., were considered and the total emission is about 42,995.93 Gg. The energy sector contributes to emissions of 42,731 Gg from thermal—and diesel-based power generation. The residue available from the agriculture sector has been quantified, which shows the northern districts of the state have higher residues greater than 6000 tons per year, and the emissions respective residue burning account to greater than 1 Gg. Emissions due to the crop residue burning are about 2222.25 Gg (Fig. 18).

Considering the contribution of crop burning to atmospheric pollution as well as likely increase in GHG, there is a need to prohibit this practice of crop residue burning unless the burning is for the purpose of disease control or the elimination of plant pests, the disposal of straw stack remains or broken bales, for education or research. Retention of crop residues in the respective agricultural field after harvesting is an effective antierosion measure. The crop residue has alternative uses such as fodder, ethanol production, energy, paper and pulp industry, manure, etc. Barriers to commercial utilization of crop residues include dispersed generation, transportation cost, etc. However, with the incentive and support from the government would help in the conversion of agricultural residues to viable products while mitigating carbon emissions from burning. Figure 19 gives the distribution of livestock in Belgaum, Yadgir, Hassan, Mysore, Haveri, and Tumkur districts. The emission from livestock assessed for enteric fermentation and manure is about 2963 Gg. The farmers are growing paddy in all the districts and the larger area under paddy is in North Karnataka districts (Fig. 20). CH_4 emissions associated with paddy cultivation are about 19,215

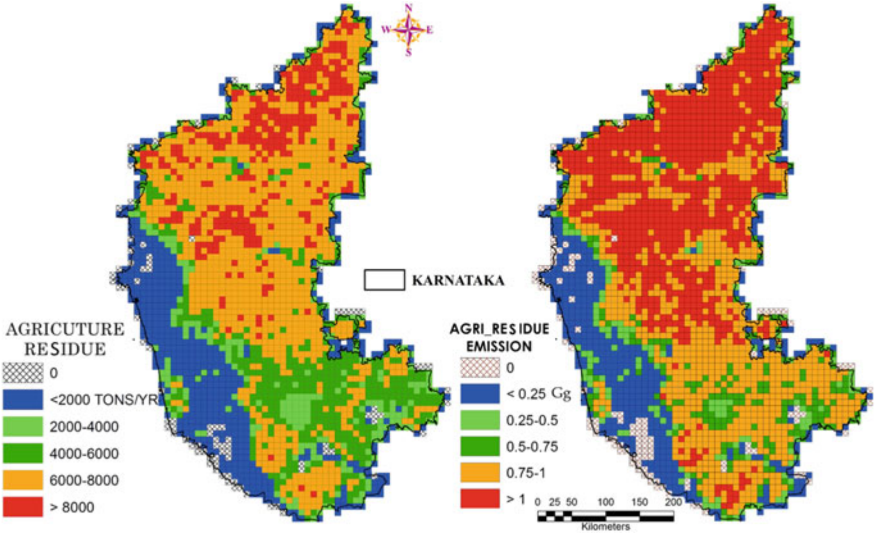


Fig. 18 Residue quantity and emission from agriculture sector. *Source* Author

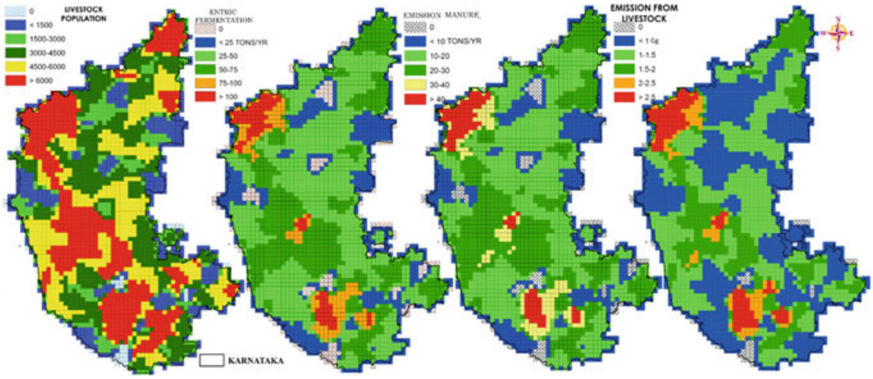


Fig. 19 Livestock population and its emission. *Source* Author

Gg (CO_2 equivalent) and Bagalkot, Raichur, Bellary, Gadag, Gulbarga districts have higher contributions toward emission from the livestock sector.

The emission due to the fuelwood burning in the domestic sector of a rural household is about 1138 Gg and Fig. 21 illustrates that Belgaum, Udupi, Dakshina Kannada, Kodagu, and Dharwad districts are with the higher fuelwood consumption (Fig. 21). The waste generated in households of Karnataka state is about 2,91,451 tons per year, which contributes emissions of 3886.72 Gg. Figure 22 demonstrates that major cities (Bangalore, Mangalore, Mysore, Dharwad) and towns (Shimoga,

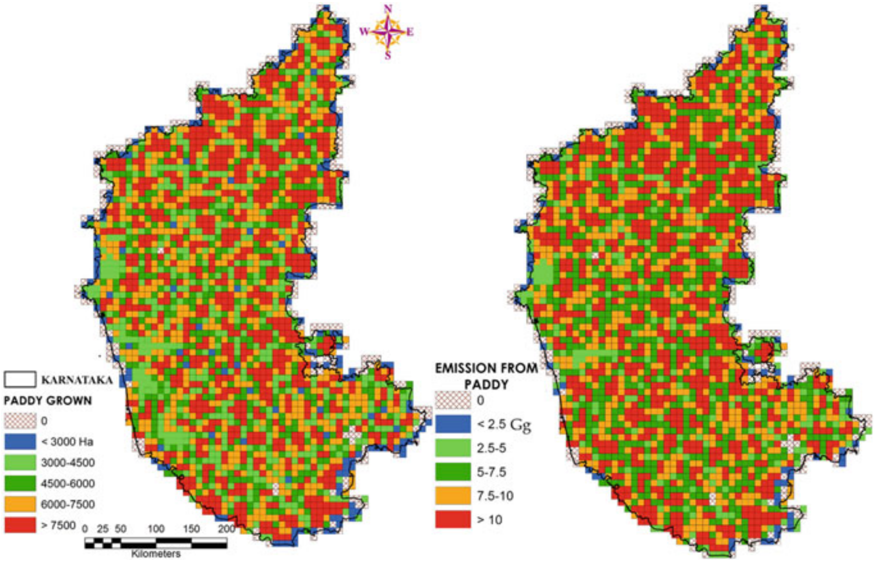


Fig. 20 Paddy grown in Karnataka and its associated emission. *Source* Author

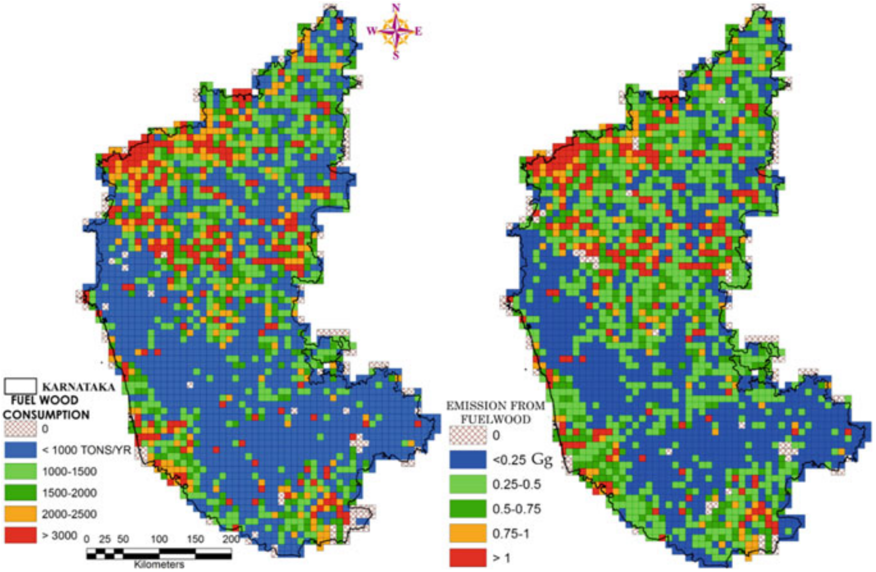


Fig. 21 Fuelwood consumption and its associated emission. *Source* Author

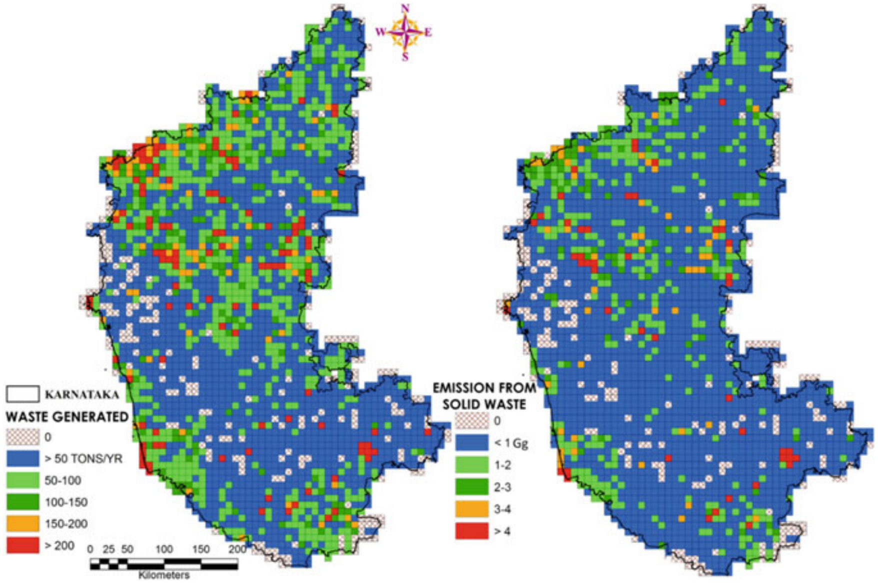


Fig. 22 Waste generated from households and its emission. *Source* Author

Bellary, Tumkur) of the state contribute significantly to the emission. due to indiscriminate disposal. Wastewater generated in urban areas is either partially treated or untreated and is discharged to the water bodies. Figure 23 presents the emission from wastewater indicating higher emissions from the major cities. Emissions from the transportation sector include CO_2, CO, NO_x, CH_4, SO_2, PM, HC, which accounts to 38,440.56 Gg. Figure 24 illustrates the spatial distribution of emission from the transport sector in Karnataka with the major contributions from Bangalore, Kolar, Chikballapur, Tumkur and Mysore districts due to higher number of vehicles.

4.4 Carbon Ratio (CR) or Carbon Status in Karnataka

The carbon status of a region or carbon ratio (CR) refers to the ratio of sequestered carbon in the ecosystems to emissions aggregated from all sectors or activities. CR values greater than 1 indicate carbon sequestration higher than emissions. Grid-wise carbon sequestration and emission were computed for 2019. Figure 25a and b give the grid-wise carbon sequestration and emissions during 2019. The annual sequestered carbon is about 16.1 Tg, while emission is 150.65 Tg, which highlights about 11% of the emission is sequestered by forest ecosystems in Karnataka. The districts or grids in the Western Ghats region have good sequestration potential with the least emissions compared with other regions. High carboemitting districts include Bangalore, Mysore, Dharwad, Bellary, and Raichur. CR ratio computed grid wise is

Fig. 23 Emission from domestic waste water. *Source* Author

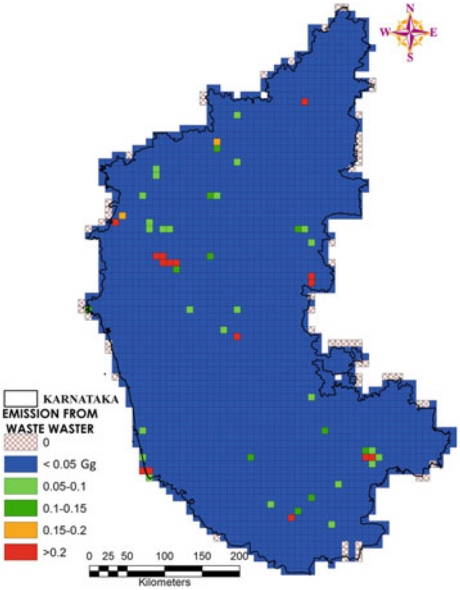
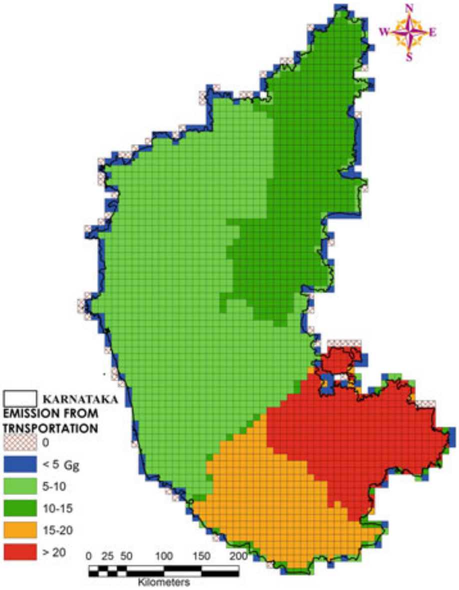


Fig. 24 Emission from transport sector. *Source* Author



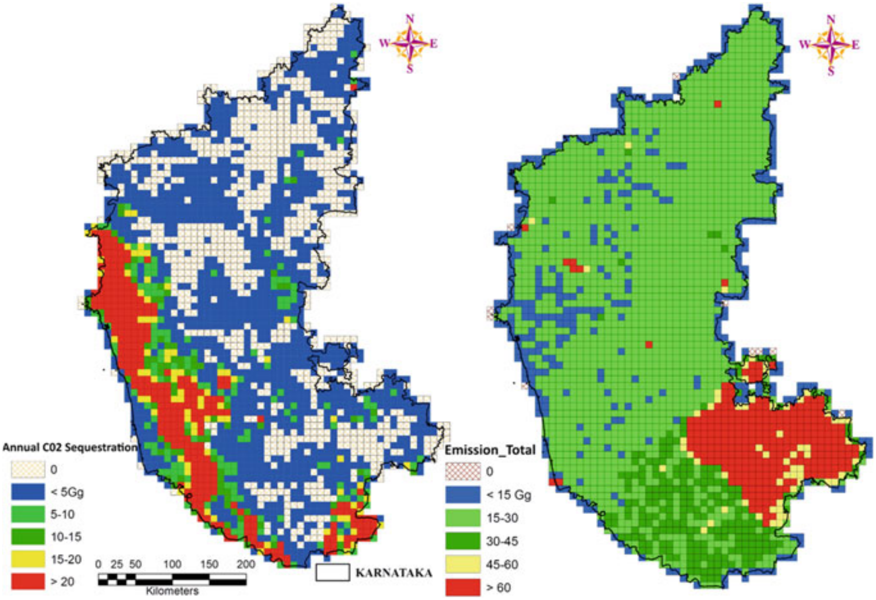


Fig. 25 Annual carbon sequestration and emission of Karnataka. *Source* Author

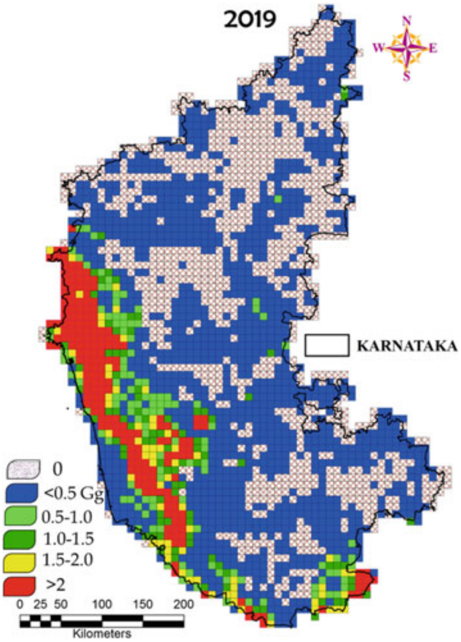
depicted in Fig. 26 highlights of CR > 1 for grids covered in the districts of Uttara Kannada, Kodagu, part of Dakshina Kannada, and Udupi. The other grids are with lower CR (≤ 0) indicating carbon-negative situation.

The study emphasizes the need to evolve appropriate policies to decarbonize through prudent afforestation policies to mitigate emissions. Afforestation with native species will not only aid in the carbon sequestration but also enhances hydrological and food security services, evident from the existence of perennial streams in the catchments dominated by native species compared with the seasonal or intermittent streams in either degraded catchments or catchments dominated by monoculture plantations. Also, due to pollination services with the presence of diverse pollinators, the crop productivity in agriculture is higher compared with the degraded landscapes highlighting the linkages of water availability, food security, and carbon security with the land cover dynamics.

4.5 Strategies for Carbon Mitigation

The strategies for carbon mitigation covering local and global perspectives would aid in framing prudent policies toward the sustainability of natural resources. Realizing the increase in greenhouse gas emissions due to the accelerated deforestation process has necessitated the measures toward adaptation and mitigation strategies for global

Fig. 26 Carbon ratio for the year 2019. *Source* Author



warming and climate change. Conference of the Parties (refer to the countries) signed up to the 1992 United Nations Framework Convention on Climate Change. Kyoto Protocol was the first global initiative proposed at 3rd Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) in 1997 to curb deforestation and promote forest conservation (Humphreys, 2008). During the 21st COP at Paris 170 countries committed to reduce greenhouse gas emissions and limit the global temperature increase to below 2 degrees Celsius (3.6 F) above preindustrial levels by the year 2100. In this regard, India pledged that 40% of power capacity would be based on nonfossil fuel sources and of creating an additional "carbon sink" of 2.5–3 billion tonnes of carbon dioxide equivalent through additional forest and tree cover by 2030.

Reduced Emissions of Deforestation (RED) has emerged as an initiative for conservation in 2005 at 11th COP meeting to support developing countries. REDD + materialized at the 18th COP proposed to offer incentives for the conservation and enhancement of the forest carbon stock and the sustainable management of forests in 2012. REDD + has been playing a significant role in forest conservation while addressing challenges and supporting direct/indirect costs involved in forest management [14]. REDD + , while providing economic benefits to the local communities, has improved natural resource management in developing countries and is a form of Payments for Ecosystem Services (PES). The conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries have been achieved with the marketing of carbon credits under the voluntary carbon standard systems through a technical procedure [27]. Carbon trading is an effective measure toward payment for ecological services, such as forest conservation, which has been established based on a rigorous valuation of these ecosystem services to encourage afforestation in a larger scale and support community livelihoods, which are at the greatest risk due to LULC change and its associated impacts. The annual sequestered carbon in forest ecosystems of Karnataka is about 16.1 Tg, which as per carbon trading accounts to be INR 34 billion ($0.5 billion) at carbon trading of INR 2142 ($30) per tonne, which highlights the scope for higher carbon credits with reforestation of degraded landscapes. In this regard, the Government of India came up with CAMPA (Compensatory Afforestation Fund Management and Planning Authority) to compensate for the loss of forest area and to maintain sustainability. The act emphasized of ecological compensation based on net present value (NPV) for the loss of forest ecosystem, while implementing developmental projects.

Although policies to implement adaptation and mitigation measures may be established at a global, national, or regional level, the consequences of climate change and the necessary adaptation have to be undertaken locally. The management options to minimize the impact of climate change include: promotion of reduced use of fossil fuels and development of clean energy; efficient use of water resources; developing low-cost sustainable technologies; improving health care and pest control; developing and using drought-resistant crops; constructing disaster-resistant buildings and infrastructure. Renewable energy sources include solar power, wind, waste to energy, are to be promoted through incentivized mechanism across all levels. The creation of people's nurseries under benefit sharing in accordance with the various forest regulations and provisions and Forest Dweller's Act, 2006, is recommended to get location-specific species saplings would enhance the rural employment opportunities. The fencing of blocks of forest lands with basal areas of less than 15 sq. m each, for minimum periods of 8–10 years, will prevent the entry of domestic cattle and humans into these protected blocks and pave the way for natural regeneration of especially native species of plants. Carbon reduction is achieved by promoting alternative materials of least carbon footprint, efficient recycling technologies, and remanufacturing as well as recovering the virgin materials. Increased emphasis on research, education, training, and awareness needs to be provided to the employees to make aware all advanced/alternative energy technologies for reducing emission through nongovernmental organizations (NGOs) and public–private participation.

5 Conclusion

Forest ecosystems have been playing a key role in the global carbon cycle and Earth's climate by capturing, storing, and cycling carbon. Plants and soils in forest ecosystems drive the global carbon cycle by sequestering (storing) carbon dioxide through photosynthesis. The sustained anthropogenic pressure has been contributing to GHGs in the atmosphere, contributing to the alterations in the climatic conditions regime due to global warming. The land-use dynamics analyses using temporal remote sensing data reveal a loss of 6% forest cover during 1985–2019 in the state of

Karnataka with an increase in built-up and agriculture areas. The total AGB of forests is about 1013.7 Tg (Teragram) with stored carbon of 506.8 Tg (in 1985) which is now reduced to 678 Tg and 339 Tg, respectively (2019). The temporal decline of AGB values in the districts of Kodagu, Shimoga, Uttara Kannada, and Dakshina Kannada is due to anthropogenic pressure. The districts of Uttara Kannada, Kodagu, Udupi, Chikmagalur have higher carbon sequestration potential due to high forest cover as compared with the other parts of the state. Forest ecosystem sequesters 11% of emissions. The industrial activities (29%), energy generation (28%), transportation (25%), and paddy cultivation (13%) are the major contributors to the total emission of the state. The grids of Western Ghats have good sequestration potential with the least emission as compared across the other regions. The state is contributing 5% GHG emissions of India's total and signifies the necessity of policy interventions. The study has further suggested improving the carbon sequestration potential by various management initiatives such as promoting reduced use of fossil fuels; increasing forest cover by large scale afforestation with native species, providing employment to the rural women for creating nurseries, effectively managing water resources; promoting alternative or developing inexpensive materials and sustainable technologies for reducing carbon footprint; promoting drought-resistant native crops; developing disaster-resilient buildings and other infrastructure.

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Annexure-I

The major industries of Karnataka (Figure A) and their installed capacity have been shown in Table A and their respective emissions.

Industries considered and their emissions

Sno	Latitude	Longitude	Industry	Installed capacity Tons	CO_2 Emission Gg
1	13.830	75.702	Visvesvaraya Iron and Steel Plant (VISL)	98,280	62.41
2	13.841	75.701	Visvesvaraya Iron and Steel Plant (VISL)	216,000	137.17
3	12.359	76.630	Mysore steel	150,000	95.26
4	15.177	76.666	JSW Steel, Hospet	12,000,000	7620.43
5	15.337	76.253	Kalyani Steels Ltd (KSL)	290,000	184.16
6	15.308	76.212	Xindia steels	800,000	508.03

(continued)

(continued)

Sno	Latitude	Longitude	Industry	Installed capacity Tons	CO_2 Emission Gg
7	12.927	74.823	KIOCL Panambur	140,000	88.91
8	13.055	77.484	Jindal Nagar, Tumkur Road Unit-1	92,000	133.54
9	13.218	77.255	Jindal Aluminium Limited-RMD, Yedehalli	40,000	58.06
10	15.906	74.540	Hindalco Yamanapur, Belgaum	350,000	508.03
11	16.113	74.520	SQuAD Forging India Private Ltd	22,000	31.93
12	12.866	77.459	Devkiran Paper Mills Private Ltd	25,000	11.34
13	15.252	74.629	West Coast Paper mill	320,000	145.15
14	13.826	75.713	Mysore Paper mill	105,000	47.63
15	12.158	76.684	South India Paper Mills	200,000	90.72
16	15.219	76.784	ACC Kudithini Cement Works	1,100,000	628.69
17	17.059	76.982	ACC New Wadi Cement Works	3,500,000	2000.36
18	13.498	77.510	ACC Thondebhavi Cement Works	1,660,000	948.74
19	17.054	76.978	Wadi Cement Works	2,590,000	1480.27
20	16.314	77.357	Ashtech India Pvt Ltd	500,000	285.77
21	16.177	75.681	Bagalkot Cement & Inds.Ltd	300,000	171.46
22	17.159	77.293	Cement Corporation of India Ltd-Kurkunta	200,000	114.31
23	17.370	77.447	Chettinad Cement -Kallur	2,500,000	1428.83
24	16.205	75.210	Dalmia Cement (Bharat) Ltd - Belgaum	2,500,000	1428.83
25	13.495	77.044	Hebbal Cements	200,000	114.31
26	13.270	76.723	Heidelberg Cement India Ltd- Ammasandra	570,000	325.77
27	12.970	76.119	Hemawati Cement Industries	200,000	114.31
28	16.205	75.300	J.K. Cement Ltd—Muddapur	1,824,385	1042.69
29	15.180	76.700	J.S.W. Cement Ltd—Vijaynagar	600,000	342.92

(continued)

(continued)

Sno	Latitude	Longitude	Industry	Installed capacity Tons	CO_2 Emission Gg
30	17.302	77.435	Kalburgi Cement Pvt Ltd	2,750,000	1571.71
31	17.161	77.294	Kesoram Cement—Vasavadatta	5,160,000	2949.11
32	17.105	77.135	Orient Cement-Chittapur	3,000,000	1714.60
33	16.227	75.198	Ratna Cements (P) Ltd, Yadwad	160,000	91.45
34	17.042	77.222	SHREE CEMENT LIMITED—KODLA	3,000,000	1714.60
35	16.194	75.492	Shri Keshav Cements and Infra Ltd.—Kaladgi	330,000	188.61
36	16.205	75.299	Shri Keshav Cements and Infra Ltd.—Naganapur	330,000	188.61
37	15.351	76.264	UltraTech- Ginigera Cement Works (G)	1,300,000	742.99
38	17.139	77.178	UltraTech- Rajashree Cement Works	3,200,000	1828.90
39	12.984	74.845	Mangalore Refinery and Petrochemicals Limited	16,300,000	11,829.81
40	12.347	76.569	Venlon Enterprises Limited	35,200	25.55
Total Emission (Gg)					42,995.93

Annexure-II

The energy produced by various power stations (Figure B) and their capacity are shown in Table B with emissions.

Thermal and Diesel power stations and their installed capacity

Sno	Latitude	Longitude	Power Stations	Installed capacity MW	CO2	CO	Emission total Gg
(a) Thermal Power Stations							

(continued)

(continued)

Sno	Latitude	Longitude	Power Stations	Installed capacity MW	CO2	CO	Emission total Gg
1	16.350	77.343	Raichur Thermal Power Station 1–7 Unit	1470	6619.87	46.73	6666.60
2	16.379	77.339	Raichur Thermal Power Station Unit-8	250	1125.83	7.95	1133.77
3	15.190	76.723	Bellary Thermal Power Station Unit-I	500	2251.66	15.89	2267.55
4	15.210	76.724	Bellary Thermal Power Station-Unit-II	500	2251.66	15.89	2267.55
5	15.207	76.713	Bellari Thermal Power Station Unit-III	700	3152.32	22.25	3174.57
6	16.379	77.339	Godhna Thermal Power Station Chhattishgarh Thermal Plant(Pit Head)	1600	7205.30	50.86	7256.16
7	13.227	74.789	Udupi Power Plant	1200	5403.97	38.15	5442.12
8	16.295	77.357	Edlapur Thermal Power Station	800	3602.65	25.43	3628.08
9	16.295	77.357	Yermaras Thermal Power Station	1600	7205.30	50.86	7256.16
(b) Diesel based power generating stations							
10	13.116	77.583	Yelahanka Diesel Generating Station	108	486.36	0.00	486.36

(continued)

(continued)

Sno	Latitude	Longitude	Power Stations	Installed capacity MW	CO2	CO	Emission total Gg
11	12.776	77.422	Bidadi Gas Based Combined Cycle Power Plant	700	3152.32	0.00	3152.32
Total emission (Gg)							42,731.23

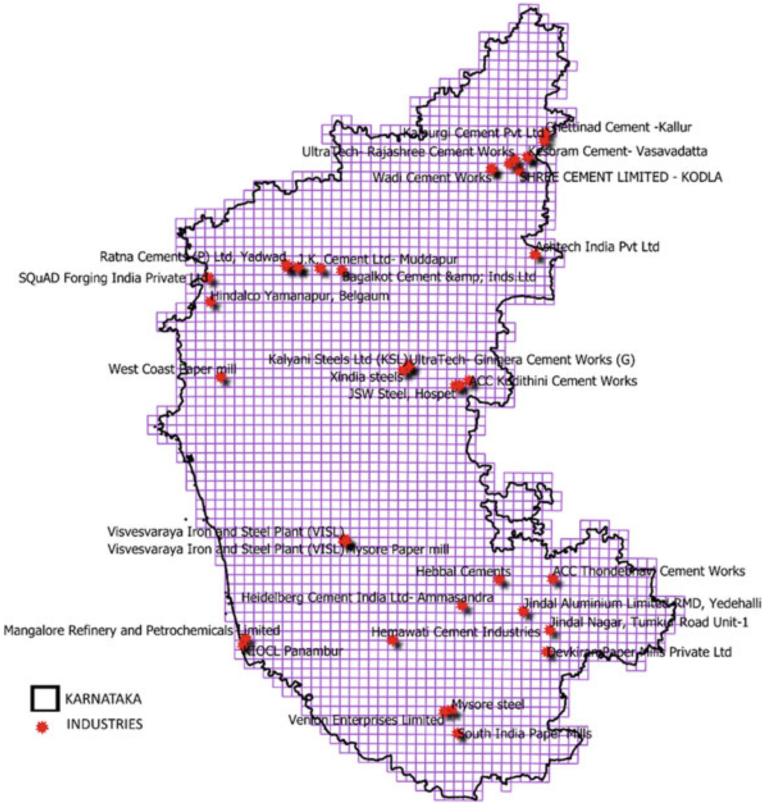

Fig. A Major industries of Karnataka. *Source* Author

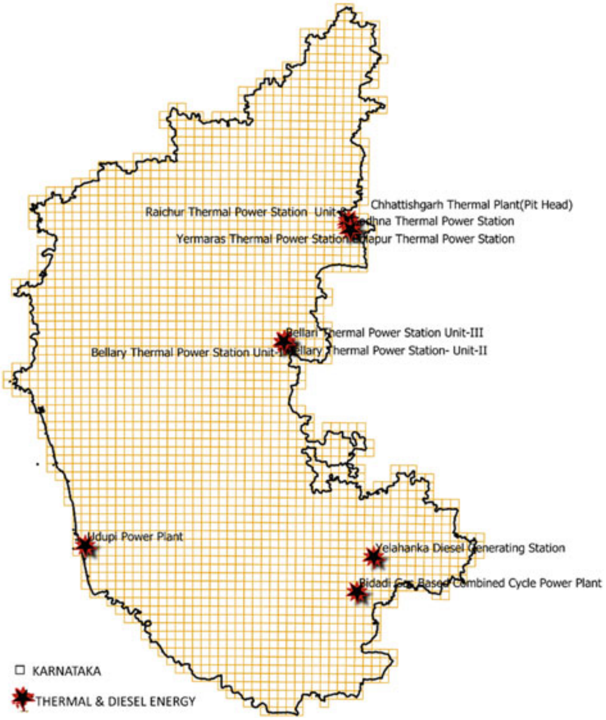

Fig. B Thermal and Diesel power stations of Karnataka. *Source* Author

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An Overview on Costs of Shifting to Sustainable Road Transport: A Challenge for Cities Worldwide

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Abstract The transport sector plays a fundamental role in economic and social development in the urban context; however, it has a significant impact on air pollutants and greenhouse gas emissions and the natural resource depletion. Therefore, this chapter seeks to identify, through a bibliographic review on road transportation and the Sustainable Development Goals, synergies and trade-offs between climate policies and transportation. Some actions to mitigate the impacts of road transportation on the environment were identified, based on the ASI (Avoid, Shift and Improve) approach considering aspects as high energy efficiency, low pollution and high capacity. Finally, this chapter presents some mitigation measures for the road transportation based on six categories and discuss the cost of shifting to road sustainable transport, which is a gap in the current literature. The results indicate that it is necessary to establish a rational transport structure with a good governance, opportunities for finance, transparency and a medium and long-term vision, prioritizing actions to incentive active transportation, that in general, has low-medium costs, in comparison to great transformations in the infrastructure of cities to implement Metro and Light-rail transit (LRT) systems, for example, that is also urgent and has a (very) high cost. All actions are important to promote sustainable cities toward a low carbon transport.

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Keywords Road transportation · Greenhouse gas emissions · Resource depletion · Sustainable development goals · Mitigation actions · Climate policies · ASI approach · Costs

1 Introduction

The transport sector has a fundamental function in the economic development and well-being of a society, being considered the life force of cities in acknowledgment of this critical role [94], however, it is the sector that fastest growing in terms of Greenhouse Gas (GHG) emissions in the world. The modest efforts of the global transport industries to gradually decarbonize the sector are not enough and the world has seen continued growth in emissions over the last years [104, 30], due to low participation of renewable energy and great dependence on fossil fuels [61].

Compared to any other economic sector, transportation accounts for about 20% of all energy used and around 23% of direct carbon dioxide (CO_2) emissions from combustion of conventional fuels (mainly diesel and gasoline). Furthermore, without targeted measures to reduce the dependence on fossil fuels and increase the use of renewable energy, the sector's emissions could double by 2050 [75].

Particularly, road transportation is the largest energy consumer, involving 75% of the total energy demanded in the transport sector in 2015 (where 75% was associated with passenger vehicles and 25% with freight vehicles) and representing 80% CO_2 emissions [36]. Road vehicles—cars, trucks, buses and two- and three-wheelers—account for nearly three-quarters of transport CO_2 emissions [37]. Urban buses are a significant source of pollution, impacting local air quality and global carbon emissions [12].

The transport sector, mainly road transportation, is responsible for a large portion of CO_2 emissions, and is recognized to be one of the main causes of global warming and climate change [35]. Thus, it is important to define decarbonization strategies for the sector translating it in a concrete medium long term action plan consideration of the drivers of sectoral transformations to achieve the sustainable development [9].

Thus, curbing transport sector emissions through innovative technologies, reduce energy for transport, electrify transport, fuels substitution (bioenergy, hydrogen, for example) and modal shift are sustainable strategies for decarbonize the transport sector, and key components of addressing climate change [39, 85].

Investments in sustainable transportation could lead to fuel savings and lower operational costs, decreased congestion and reduced air pollution. Additionally, it is estimated that efforts to promote sustainable transport can deliver savings of up to US$70 trillion by 2050 [91].

In accordance with the principle of 'common but differentiated responsibility' and 'respective capabilities' set out in the United Nations Framework Convention on Climate Change (UNFCCC), developed country Parties are to provide financial resources to assist developing country Parties in implementing the objectives of the Convention [86].

New technologies are improving the efficiency of existing transport methods and will positively affect both passenger transport (public and private) and freight transport. Connected and Autonomous Vehicles (CAVs), for example, incorporate many technologies to enable driverless, safe, and efficient transportation reducing traffic congestion, crashes in roads, air pollutants and GHG emissions [21, 64, 65].

In addition, several initiatives have sought to develop the Battery Electric Vehicle (BEV) and the fuel cell as alternatives to vehicles with internal combustion engines and to establish fuels such as biofuels, natural gas, Liquefied Petroleum Gas (LPG), hydrogen, and electricity as options to replace conventional liquid fuels [31, 45, 61].

Non-technological measures to encourage the use of healthy means of transport, such as active transportation (walking and cycling) and better urban planning based on resilient public transport systems with low emissions, can promote healthy environments, facilitating healthy physical activity and, as benefit, many of these strategies can save considerable health costs [95].

Some cities have focused on strategies to facilitate active mobility and non-motorized transport, which clearly have emission implications. It could be an opportunity to retrofit the infrastructure of cities and move toward a low carbon transport. The recent pandemic due Covid-19 brings a big debate on transportation, high population densities in cities and how it facilitates spread. This is demanding a very rapidly growing of the peer-reviewed literature on cities and Covid-19 disease. It is very important to consider sustainability issues as Sustainable Development Goals (SDGs) when the development of responses policies and plans to Covid-19, as a cross-cut strategy to enhance safe public transport and promote smart cities [44].

However, all these possible strategies to mitigate the impacts of the transport sector on the environment and in the quality of life of society have a cost for their implementation. Therefore, studies should be developed that seek to identify the relationship between the cost necessary to achieve sustainable transport and the co-benefits derived from reducing these impacts, as well access for finance opportunities and new governance tools and models.

Many countries are committed to pursuing limiting global warming to below 1.5 °C, as detailed in the 2015 Paris Agreement. However, the mitigation cost of achieving GHG emissions in 2030 with 1.5 °C pathways has been projected to be at least 5–6 times higher than the cost of achieving the Nationally Determined Contributions (NDCs) [105].

Thus, this chapter aims to identify, by means of a bibliographic review, the main actions for mitigating the impacts of the road transportation on the environment, as well as estimating the cost of shifting to road sustainable transport. We emphasize that this study seeks to address a gap in the literature resulting from the low frequency of research that seek to analyze the cost to achieve sustainable transport.

To achieve these objectives, in addition to this introductory section, this chapter is structured as follows. Section 2 deals with the methodology. Section 3 deals with the intrinsic relationship between the SDGs and road sustainable transport. Section 4 outlines some possible actions to mitigate impacts on road transportation and Sect. 5 presents and discusses the costs necessary to make it sustainable. Finally, Sect. 6 highlights the conclusions and presents recommendations for future works.

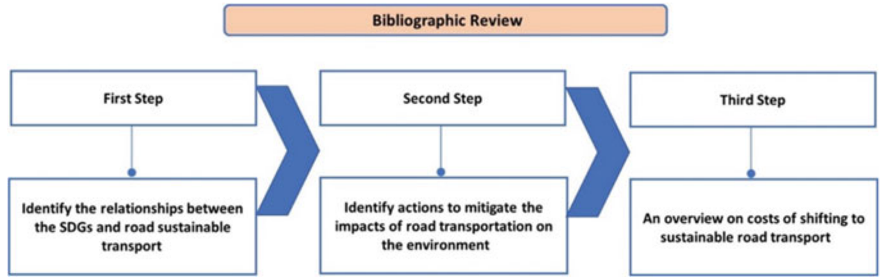

Fig. 1 Bibliographic review steps

2 Methodology

The methodology, developed to achieve the objectives of this research, is based on an extensive bibliographic review, and follows the steps identified in Fig. 1. In the first step, we seek to identify the relationships between the SDGs and road sustainable transport, as well as highlighting the need for study on synergies and trade-offs of actions taken to promote a low carbon transition in the sector addressing sustainability.

In the second step, we seek to identify actions to mitigate the impacts of road transportation on the environment (for example, increased GHG emissions and natural resource depletion), based mainly on the ASI (Avoid, Shift and Improve) approach. In the third step, we performed an overview on costs of shifting to road sustainable transport by implementing some of the mitigation actions identified in the second step.

It is worth mentioning that the bibliographic review carried out in this chapter included direct searches for relevant scientific articles in databases such as Web of Science, Scopus and Google Scholar, as well as encompassing a documentary search in technical reports developed by renowned institutions such as the International Energy Agency, Institute for Transportation and Development Policy and Inter-American Development Bank.

3 Road Sustainable Transport and the Sustainable Development Goals

As cities grew, expanded transport networks promoted urban development, but also created a series of challenges to achieve sustainability, assuming a paradoxical role [60]. The current level of motorized transportation worldwide due to reliance on cars is increasingly a social, environmental and economic problem [5]. Modern cities continue to suffer with traffic congestion where a lot of resources are consumed in this process, resulting in an ecological environment and a transport system on the brink of collapse [99].

The transport sector will be playing a particularly important role on track to achieving the Paris agreement, given the fact close to a quarter of energy related global GHG emissions come from transport [12]. In most cases, safe, clean, sustainable and equitable transport systems help countries especially in cities and urban centers to thrive [4].

Therefore, given the importance of the road transportation in terms of energy consumption and CO_2 emissions as mentioned before, a rational and subnational traffic structure based on the concepts of sustainable development should be established, considering high efficiency, low-energy, low pollution and high-capacity to solve, or at least minimize, the problems arising mainly from motorized transport [99].

In addition, it must include a broad implementation of sustainable transport policies, including economic and regulatory instruments, physical and flexible measures (infrastructure improvements in road transportation, including land use and public transportation), and technological innovations, without compromising the mobility of goods and people [72].

In the 2030 Agenda for Sustainable Development, sustainable transport is mainstreamed across several SDGs and targets, mainly to: Objective 7 (affordable and clean energy); Objective 9 (industry, innovation and infrastructure); Objective 11 (sustainable cities and communities); Objective 12 (responsible consumption and production); and Objective 13 (climate action) [90, 88].

The importance of transportation for climate action is recognized under the UNFCCC and a climate treaty may help meeting some of the SDGs, but there may also be trade-offs and synergies between the co-benefits of climate change mitigation strategies, as shown in Fig. 2. Links between sustainable development, transportation and climate policies.

Climate change mitigation policies have several types of impacts, both positive (co-benefits) and negative (adverse side-effects), including in relation to the

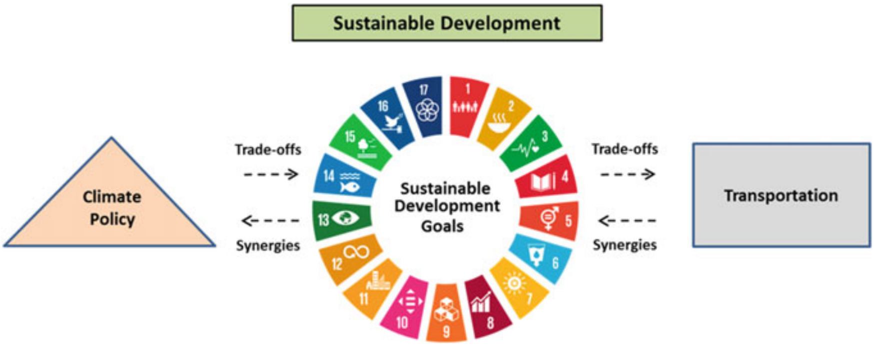

Fig. 2 Links between sustainable development, transportation, and climate policies

SDGs. Thus, a successful integration of climate mitigation policies also requires a comprehensive understanding of the adverse side-effects, causing greater synergy between the SDGs, especially regarding Goal 10 (reduce inequality within and among countries) [58, 59].

For example, policies that encourage energy efficiency in the transport sector, that is, transition to a low carbon future, have several co-benefits such as improving air quality and reducing natural resource depletion. However, it can lead to unemployment in the fossil fuel industry or other sectors of the economy that can be negatively affected by carbon prices [15].

Even so, many opportunities on creating green jobs specially related to renewable energy and energy efficiency sectors are increasing [79]. Therefore, strategic thinking and government support can be used to minimize the long-term adverse consequences of the transition to a low carbon economy for repurposing obsolete sites and retraining newly unnecessary workers, for example [59].

In addition, incentives for stockholder and a coherent transition and diversification strategy based on the skills of the existing workforce are fundamental to facilitate the process of economic restructuring and mitigate the effects of transformation of existing industrial, institutional, social and technological structures [15].

Complementarily, Fig. 3 indicates that several development pathways can be adopted to promote a low carbon transition and sustainability, however, it is important to take into account that all decisions and possibilities must prioritize strategies that maximize all synergies between the SDGs and targets for the transport sector, especially those related to clean energy and climate action.

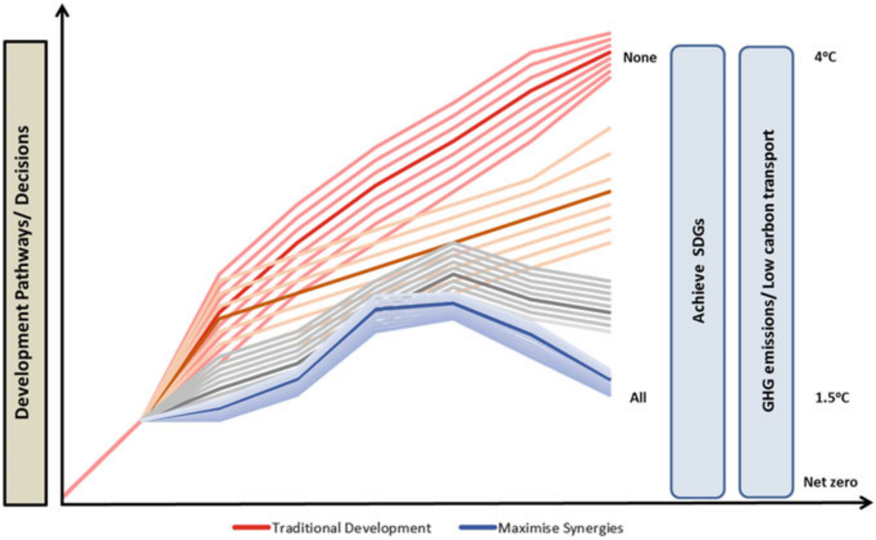

Fig. 3 Development pathways for a low carbon transition

The adoption of policies and action plans, as the NDCs submitted by countries under the Paris Agreement are examples of how to pursue efforts addressing a sustainable development path transformation. However, it is necessary increase ambitions in their actions by national and subnational levels and non-state to maintain a reasonable chance of meeting the target of keeping warming well below 2 °C [69].

The momentum to promote sustainability is urgent, considering the global warming and the many impacts of climate change presented now and, in the future, economic and political crisis, including new challenges presented due to COVID-19 pandemic. The more vulnerable cities located in developing countries have opportunities to rethink the design, transport systems, promote disruptive technologies and industries in a global effort to promote a low carbon development worldwide.

4 Mitigation Options for Road Transportation

In order to promote sustainable urban transport and facilitate active mobility and non-motorized transport, in this section are presented the main strategies on mitigation actions, which are essential to achieve SDGs and targets established in policies and action plans.

4.1 International Aspects of Mitigation Policies for Transportation

According to the 24th session of the Conference of the Parties (COP-24) at the International Transport Forum's Annual Summit, occurred in 2019, transportation plays an important role in achieving the objectives of the Paris Agreement thus, low carbon transport policies are required to achieve the 2 and 1.5 °C targets [105], considering the climate emergency and necessity of mitigation actions to contain transport-related climate change [62].

A comprehensive analysis of international and national climate policies for road transportation is lacking. In this chapter are presented some measures to support policymakers at the national and international levels who are concerned about rising GHG emissions.

An important contribution to solve, or at least minimize, problems related to climate change is to promote synergy between mitigation and adaptation, that is, adaptation corresponds to the way defined to make the transport system more resilient and that contributes in the best way to promote an effective management of disaster risks. Already mitigation allows decision makers in developing countries to develop transport strategy that support the minimization of climate change, increasing the efficiency of transport systems [26].

However, a mitigation action can be conceptualized in different ways by different authors, that is, Tyler et al. [82] define it as any activity that contributes directly and/or indirectly to the reduction of GHG emissions, as it generates concerns as for the promotion of sustainable development in cities [66], which are places of high energy consumption as fossil fuels, generated mainly by the expressive use of road transportation [37].

Based on the principles that govern road sustainable transport, it is essential to define and adopt measures that are capable of meeting, from a local road traffic regulation project, an urban planning strategy to promote public transportation in a city to a national policy, as advocated by Nationally Appropriate Mitigation Actions (NAMA) in the pre-2020 context and from now with the NDC under the Paris Agreement [6], and reinforced by United Nations Economic Commission for Europe (UNECE), adopt effective public interventions to reduce CO_2 emissions, and adaptation measures are essential to reduce vulnerability to climate change [84].

In addition, Singh et al. [76] also consider that mitigation actions correspond to interventions and commitments, including targets, policies and projects, undertaken by a government or other entity to reduce GHG emissions, such as: (i) National Climate Plans, (ii) policies that establish emission standards for vehicles, regional emissions trading systems; and energy production policies from renewable and sustainable sources (for example, palm oil production); and (iii) NDC.

According to the definitions of NDCs prepared by countries, 91% of contributions attributed and directed to passenger transport are observed, with urban transport corresponding to 74% of these measures [32]. To achieve the targets set by NDCs, mitigation measures in the transport sector may include actions to reduce or minimize and manage the demand for travel, shift demand to low carbon modes or maintain their participation and/or improve technologies and fuels vehicles, using the Avoid, Shift and Improve (ASI) approach [27].

The "Avoid" strategies describe measures to reduce motorized trips and travel times; "Shift" strategies shift travel activity to more energy efficient modes; and the "Improve" strategies focus on increasing the energy efficiency of vehicles and decarbonizing energy sources [32].

According to SUTP [70] and Farzaneh et al. [22], the ASI approach assists in determining the right action plans and policy interventions to achieve a sustainable urban transport system as described in Fig. 4.

For the ASI approach to fulfill its role in contributing to the emission reduction, mainly of GHG, it is necessary to define which strategies will be adopted, since the need to provide clean, decarbonized and efficient transportation is the key to solve many challenges that cities are facing, due to their high connection with developments in urban energy systems [102].

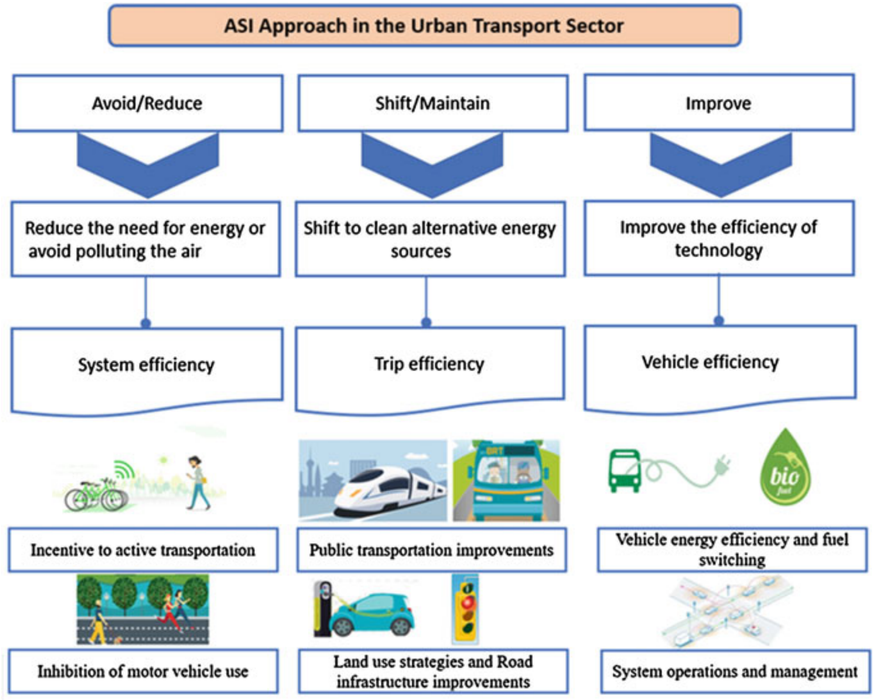

Fig. 4 Structure of the ASI approach. *Source* Adapted from SUTP [70], IDB [33] and Farzaneh et al. [22]

4.2 *Opportunities for Cities Toward a Low Carbon Transport*

As mentioned previously road transportation including public and private transportation has a great participation in terms of GHG emissions in cities [102]. Mitigation options consider to incorporate high penetration of resource-efficient technologies to support a transition to a low carbon electricity supply consistent with 2 °C climate mitigation scenarios [81]. A review of the transport mitigation actions listed in NDCs from developing and emerging countries showed that the distribution of mitigation actions has a strong focus on fuels and vehicles, and urban transport infrastructure such as road and rail is another area that was highly recognized [56].

Individual transportation is based on pedestrian or automobile traffic through individually transport, such as bicycles, motorcycles or cars [52], whereas the urban road public includes a variety of options such as buses, Bus Rapid Transit (BRT) and regional taxis [54].

There are climate investment funds from public and private initiatives dedicated to the transport sector. Among these initiatives, the Green Climate Fund (GCF), which is a climate finance entity, founded by the UNFCCC in 2010, is dedicated to long-term project development strategies, including low carbon transport [50].

The need to provide clean, decarbonized and efficient transportation is the key to solving many challenges that cities are facing, due to their high connection with developments in urban energy systems. For this, it is necessary to avoid, through urban planning policies, that the need to use cars is reduced [102].

In order to be able to face the challenges and promote road sustainable transport, it is necessary to comply with certain principles, such as: (i) planning dense cities in such a way that transportation serves only to support the population and not a main actor; (ii) develop traffic-oriented cities to ensure urban connectivity and enhance land use; (iii) optimize the network and use of highways, ensuring that traffic rules are adopted and applied; (iv) encourage walking and cycling (active transportation); (v) implementing improvements in traffic; (vi) control the use of the vehicle; (vii) manage parking lots; (viii) promoting the use of clean vehicles; (ix) promoting communication solutions; and (x) addressing the challenges comprehensively [71].

Therefore, to guarantee sustainable urban transport and meet the needs of projects at various levels, including urban environments, it is important to determine the right action plans and political interventions through criteria that promote ASI approach indicated by actors such as Inter-American Development Bank (IDB).

In order to meet the principles for making urban transport sustainable from an ASI approach, mitigation actions for urban road transportation are based on the study of IDB [33]. Therefore, mitigation actions categories are divided into: (i) Public transportation improvements, (ii) Incentive to active transportation; (iii) Inhibition of motor vehicle use; (iv) Land use strategies and Road infrastructure improvements; (v) System operations and management; and (vi) Vehicle energy efficiency and fuel switching, and described in Table 1.

According to the mitigation actions presented in Table 1, Sect. 5 seeks to describe them, as well as to provide an overview of the cost of shifting to road sustainable transport obtained through a literature review.

5 An Overview on Cost of Shifting to Road Sustainable Transport

In the last decades is increasing consensus that the growth in motorized land vehicle is causing serious environment impacts including the contribution to anthropogenic climate change. As presented in Section 1, the transport-related carbon emissions are rising and the transport sector has a crucial role to promote sustainability worldwide.

There is also a concern that energy intensity of land transport correlates with its adverse health effects as urban air pollution, physical inactivity, road-traffic injuries and environmental degradation. Today, the world faces a big challenge: how to shift the conventional transport modes to a more sustainable? According this necessity, it is important to consider some aspects as governance, planning with short to long term measures, and an evaluation on costs to help decision makers for prioritizing sustainable adoptions.

Table 1 Categories of mitigation actions

Categories	Description
Public transportation improvements	Improvement of operational systems; improvements in the tariff system; integration of services in priority corridors; implementation of integrated BRT corridors; and renovation of the fleet through the regulation of useful life, incentives for the adoption of more efficient and cleaner vehicles and gradual elimination of obsolete vehicles
Incentive to active transportation	Improvement proposal on sidewalks and pedestrian crossings; traffic moderation as traffic calming; and improved infrastructure, networks and support facilities for bicycles
Inhibition of motor vehicle use	Automobile fuel taxes and subsidies; direct payment by drivers for the use of a road or segment of road; parking prices; street parking supply management; compressed work weeks and telework; share travel and incentives; car sharing programs; motor vehicle registration fees and taxes; Quota systems for motor vehicles; and plate restrictions
Land use strategies and road infrastructure improvements	Use of actions for urban planning and codes; transit-oriented development; car-free areas and streets with restricted traffic; construction of viaducts or underpasses, installation of traffic signs, roundabout construction or construction of a detour on the outskirts of the city
System operations and management	Eco-driving and vehicle maintenance programs; and Intelligent Transport System (ITS)
Vehicle energy efficiency and fuel switching	Use of vehicles such as motorcycles and cars more efficients; Biofuels; and electric road vehicles

Source Adapted from IDB [33]

When other co-benefits are included, such as improved energy security, many transport GHG mitigations options become more attractive. Some strategies to reduce GHG emissions are highly cost-effective and many generate cost savings over the life of an investment, as in a particular energy-saving technology (calculated using normal discount factors), for example [55]. When co-benefits are included in the cost-effective analysis, it can be an opportunity to convince policy makers and influence decision-making process.

This section aims to bring a discussion on how much is costly shifting to road sustainable transport modes, but independent of the estimates it is important to recognize that always, the cost of inaction will be higher in the future. For this, mitigation actions for urban transport based on the study of IDB [33] where considered, with an analysis of options and costs estimate to promote sustainable transportation in cities, according their capabilities and specificities.

There is an urgency to implement projects that to stay on course to keep the planet from warming more than 2 °C above pre-industrial levels. A research estimated that we will need US$2 trillion in annual global capital investment to building low carbon transport, with a US$300 billion annual saving compared to fossil-fueled business as usual scenario, which would bring 4 °C of global warming [49, 98].

The estimates presented by Lefevre et al. [49] reveal an emerging consensus that a low carbon future of infrastructure development will cost less than current high-carbon patterns of development, and significantly less over the long term. Moreover, the analysis demonstrates that a low carbon scenario is within the current means. This opens an array of new options for prioritizing sustainable transport investment. Hence, a greener path toward transport infrastructure is not only attractive as a climate change mitigation strategy, but it is also feasible, that is, within the current financial flows invested in the transport sector. In addition, it has the potential to bring more overall prosperity through financial savings. An evaluation of costs to shifting to sustainable transportation are presented according the six categories as presented as follows.

5.1 Public Transportation Improvements

The public transportation improvements aim to make it more attractive in relation to the private car use and to promote the operations with greater energy efficiency, in addition to stimulating the use of fuels with low carbon intensity [33], as further discussed in Sect. 5.6. What makes technological innovations in the system necessary, such as vehicles, track, and fuel, using advanced engine management systems, efficient vehicle transmission groups; and monitoring of standards for low-emission vehicles [84].

In addition, the implementation and improvement of the mass transport infrastructure is another way to assist in improving the journey of public transportation, providing the induction of trips in a system of greater capacity, making it possible to an increase in migration to mass public transportation and a reduction in the use of private cars, taxis and minibuses by switching to other modes leading to reduced congestion [17].

In the study by Farzaneh et al. [22], for example, it was possible to observe that the development of the BRT system is capable of generating a significant increase in the number of passengers transported per kilometer (km). Regarding the BRT implementation, in Brazil, several cities implemented the system such as Curitiba, Rio de Janeiro, Salvador and Guarulhos [3, 38, 68]. Specifically, in relation to cost, there is a variation in these locations between US$2.481 million/km (Guarulhos city) and US$14.716 million/km (Rio de Janeiro city). Thus, it is noted that there is a medium—high implementation cost this type of system, as presented in Table 2.

Table 2 Estimated costs on public transportation improvements

Examples of measures	Case study	Costs analysis	Estimated costs ($)	References
System integration in priority corridors: BRS (Bus Rapid Service)	United States (New York)	(Very) Low	Total corridor cost: US$0.276 million (2013 USD)	FETRANSPOR [19]
	Brazil (Rio de Janeiro)		Not available	FETRANSPOR [19], BRTdata [3]
Bus Rapid Transit (BRT)	Brazil (Curitiba)	Medium - High	US$7.146 million/km (year: 2013)	ITDP [41]
	Brazil (Rio de Janeiro)		US$14.716 million/km (year: 2013)	ITDP [41]
	Brazil (Salvador)		US$46 million total cost (2020)	Revista OE [68]
	Brazil (Guarulhos)		US$2.481 million/Km (year: 2013)	BRTdata [3]
	United States (Washington, DC)		Total corridor cost: US$29.1 million (2008 USD)	WMATA [96]
	United States (New York)		US$1.072 million/km (year: 2013)	BRTdata [3]
	Indonesia (Jakarta)		US$2.000 million/km (year: 2012)	C40 [11]
Light-rail transit (LRT)	Salt Lake City/TRAX	(Very) High	capital cost per mile (US$ million 2016) US$61.3	LRN [48], UTA (2020)
	United States		The average cost per km was US$38.6 million, (US$17.0 million to US$66.9 million - range from a sample of five LRT projects in the United States)	ITDP [41]; BRTdata [3]
	Indonesia (Jakarta)		US$2.290 billion	Visit Jakarta [93]

(continued)

Table 2 (continued)

Examples of measures	Case study	Costs analysis	Estimated costs ($)	References
Metro	Hanoi Metro Line 2A Stats	(Very) High	Construction Cost Per km: US$66.259 million	Clark [16],Hanoi metro [29]
	Shanghai Metro Line 1 Stats		Construction Cost Per km: US$18.634 million/US$33.168 million (2019)	Clark [16]
	Europe projects		Costs per route-kilometer (including stations and rolling stock): US$50–100 million (2002 prices)	Flyvbjerg et al. [24]
	US projects		US projects - the range is US$50–150 million	Flyvbjerg et al. [24]

In addition to BRT, there are other mass transit systems such as Light-rail transit (LRT) and Metro. We emphasize that, although these systems correspond to metro-rail transport, they directly impact cities and road traffic. As an example of cost associated with LRT, there are the five LRT projects in the United States considered by ITDP [38]. The average cost of the light-rail track was US$38.6 million/km, though the range was wide, from US$17.0 million to US$66.9 million. Regarding the metro, in Shanghai, the first subway line in the city, is now the busiest and most important north–south line in the system covering 28 stations with a implementation cost that varied between US$18.63 million/km to US$33.17 million/km [16]. These values indicate that the cost of implementing these systems is even higher than that of the BRT.

Considering all options presented in Table 2, it is important to take into account a long-term vision, and urgency to promote a transformative way toward sustainability. Many policymakers prioritize BRT based on the evaluation of a cost-effectiveness analysis and, budget, but it is important to consider electrification of buses and also the infrastructure constructed to shift to metro and tram in the future.

5.2 *Incentive to Active Transportation*

Policies of incentive for active transportation are known as attraction strategies, as they are able to attract users and seek to meet the processes of allocation, design and of space on the streets to retain travel on foot and by bicycle and also ensure that these modes are safe and attractive for everyone [33]. The increase in investment in infrastructure to promote cycling and walking and the structuring of Compact city design help to reduce the use of motorized and the duration of journey while also improving quality of life [17].

In addition, the development of non-motorized transport is able to reduce the number of passengers per km traveling in private vehicles when cycle lengths are expanded [22]. Walking and cycling are the healthiest ways to get around our cities, providing valuable physical activity for people generating indirect public health benefits by reducing the use of automobiles, thus diminishing air, water, and noise pollution and the overall level of traffic danger [67].

Cities require safe and pleasant environments for active transportation with destinations in easy reach and, for longer journeys, public transport that is powered by renewable energy, thus providing high levels of accessibility without car use. Much investment in major road projects does not meet the transport needs of poor people, especially women whose trips are primarily local and off road. Sustainable development is better promoted through improving walking and cycling infrastructures, increasing access to cycles, and investment in transport services for essential needs [101].

In terms of opportunities for bike sharing systems it is emerging a new paradigm that for the users is better pay for the service than have an own bicycle, considering some impeditive factors such as the necessity of an area for parking, maintenance, security and others. For example, a private company takes on the responsibility of providing and operating the system and takes on all risk and fundraising responsibility. Bikes have an enormous potential to connect people in local neighborhood, or in the beginning of big trips serving as a mode for the first mile in the context of intermodal connections.

Regarding improved bicycle infrastructure and networks, in Redmond city, United States, a project was launched of 28 stations of Bike Sharing with 252 bikes: 14 stations and 126 bikes at key locations downtown, and 14 additional stations in the Overlake/Microsoft campus area [2]. The implementation cost of the system for both Phase 1 and 2 corresponded to: (i) Smart Lock System equipment (US$5.79 million), and (ii) Dock Based equipment (US$7.02 million). In Brazil, the bicycle sharing system on the campus of the Federal University of Rio de Janeiro corresponds to 8 sharing stations and 60 bicycles and the five-years implementation cost was US$148,615 for the pilot project [25]. These results indicate that the cost of implementing these systems is low, when compared to BRT, LRT and Metro, for example. These and some other case studies are shown in Table 3.

5.3 Inhibition of Motor Vehicle Use

The inhibition of motor vehicle use involves: (i) the pricing motor vehicle use; (ii) the parking pricing and management; (iii) commuter travel reduction policies; and (iv) motor vehicle access and use.

Table 3 Estimative costs on active transportation projects

Examples of measures	Case study	Costs analysis	Estimated costs ($)	References
New and improved sidewalks and pedestrian crossings	Sidewalk Asphalt Paved Shoulder	Low	US$5.56 (Square Foot)	Bushell et al. [10]
	Crosswalk (High Visibility Crosswalk)		US$2,540 (each)	Bushell et al. [10]; FHWA [20]
Improved bicycle infrastructure, networks, and support programs	Bike way (Bicycle Lane)	Low-Medium	US$133,170 per mile	Bushell et al. [10]
	Bike Sharing (Redmond, Washington, United States)	Low-Medium	Smart Lock System equipment (US$5.792 million) five-years cost	Alta Planning and Design [2]
			Dock Based equipment (US$7.015 million) five-years cost	
	Bike Sharing (Brazil) university campus	Low	(US$148,615) five-years cost - Pilot project	Fundo Verde [25]

Pricing motor vehicle use are pricing ideals applied to the use of vehicles in an urban environment according to the polluter pays principle, being the party responsible for the production of pollution intended to pay for the damages caused [33]. Considering the polluter pays principle, it is estimated the costs of free or reduced-rate parking to pass on value to drivers in urban areas of the United States, whose cost of implementing parking lots varies between US$1 and US$5 per day. The charge of parking fees can be considered the first stage in urban traffic pricing system, due to the simplicity and low cost of implementation [73].

According to Dender [92], although fuel taxes are adequate to reflect the external costs of CO_2 emissions, the application of taxes should be related to the distances traveled by vehicles according to congestion, seeking to effectively reflect the damage caused on highways on roads and other infrastructure-related costs. Regarding vehicle taxes, they are increasingly used to guide consumer choices when purchasing more fuel-efficient and less polluting vehicles. The development of the Mobility Credits Integrated platform enabling travelers to improve urban transport sustainability is an example of the polluter pays principle, since it converts the amount of GHG emitted to all travelers in the area into credits, that is, the user who is negative would have to buy credit positive user [23].

Parking pricing and management refers to the setting of the appropriate price to achieve an efficient transport network, manage the supply of spaces in order to maximize the effectiveness of the space used and define requirements for parking [33]. In order for parking and management to be considered sustainable, it is necessary to comply with principles such as, setting limits for new locations chosen based on the needs of the city, creating parking lanes on local and collectors roads, and introducing paid parking areas within the urban center itself [52]. As costs for building parking lots in urban areas, Litman [54] identified a variation in construction costs between US$3,000 and US$35,000, estimated total annual cost between US$805 and US$3,903, operating cost US$350 to US$1,200 per year according to the types of facilities classified in suburban, urban and central business district.

Commuter travel reduction policies also aim to reduce the number of trips made by vehicles, especially private ones, offering employees incentives and options for traveling in different modes [33]. One way to reduce the number of trips is to adopt practices such as teleworking, which provides social, environmental and economic benefits, since the ability to work efficiently from a position outside the traditional workspace, using technological tools and communication, such as those provided by the state or private initiative, reduces the need to travel, especially in urban areas, generating less traffic flow [8]. However, it is important stimulate a behavior change, that is increasing and being experienced during the recently pandemic due COVID-19.

Regarding motor vehicle access and use is important to discourage ownership and its use, mainly through individual use; increase the likelihood of families with zero-emission cars; and reduce congestion [33]. But recent study as presented by Sperling [80] presents that in the next decades the car sharing or other services will scale-up being focused on electric vehicles.

According to Boschetti et al. [7], car sharing either through carpooling proves to be a very effective and sustainable transport solution in urban areas, as it is intended for people who have only the occasional need to use of a car and who do not wish to own one, which encourages walking, cycling and use of public transportation. Carpooling corresponds to the sharing of travel by car, an end of which a person traveled more in a car, so that travel costs, fuel costs and tolls, but most importantly, the social and environmental point of view of pollution from the air [57].

Carsharing is a system used by many users. In this case, vehicles are delivered to users through fleet operators, who charge fees according to the toll systems accessible to the public to use them [78]. According to Smolnicki and Sołtys [78] the literature on carsharing is extensive and discusses some co-benefits as impact on vehicle ownership, predicted travel emissions and economic benefits, including also driverless carsharing model. The costs of inhibition of motor vehicle use strategies are shown in Table 4.

Table 4 Summary of estimated costs on inhibition of motor vehicle use strategies

Examples of measures	Case study	Characteristics	Costs analysis	Estimated costs ($)	References
User pays principle	Urban areas in the United States	Estimates of free or reduced-rate parking costs in urban areas	Low	Cost for implementation parking US$1 to US$5 per day	Schwaab and Thielmann (2002)
Street parking supply management	Parking facility	Types facilities are classified in suburban, urban and central business district	Low	Construction Costs US$3,000–US$35,000; total cost US$805–US$3,903	Litman [54]

5.4 Land Use Strategies and Road Infrastructure Improvements

Land use strategies are tactics used to discourage the use of automobiles as the main means of transport, through proposals for practices that reduce travel times and encourage walking, making cycling and public transport more accessible and comfortable [33].

According to a study by Farzaneh et al. [22] a strategy to be adopted would be to promote the improvement of the way the Restricted Traffic Zone (RTZ) is implemented, since this practice is capable of reducing the number of passenger trips per km in private vehicles after a preventive measure that prevents unauthorized vehicles from entering the city. Cities of Scotland, capital costs for implementing Low Emission Zones include US$2,792,188 and US$21,899,115. In this case, the cost of capital is made up of the cost of design, marketing, implementation and public transport. As the hypothetical basis for calculating the cost, an area in the urban center between 0.5 and 3 km^2 is considered. Costs are classified as low, medium or high according to the size of the areas [46].

Another way indicated by Lejda et al. [52] would be the creation of walking zones, such as those totally closed to automobiles and public transportation,with limited access to passenger cars and full access to public transport; and with a total ban on the entry of passenger cars, but with access to public transport, which are essential elements of a sustainable urban transport system, as long as they are properly located and organized. On case of bicycle boulevards, as developed in the city of Portland in the United States, costs of implementing streets with low volume and low speed, require recovery as sidewalk, signage, calm traffic and traffic reduction, which corresponds to costs between US$31,135 per km and US$89,238 per km depending on the types of improvements to the road, which are considered low [100].

In many developing countries, transport services and infrastructure facilities are treated as public services or social policy instruments. However, in these environments, the prices transmitted to customers rarely reflect the cost of providing these services and facilities, as they are granted benefits such as subsidies and the absence of commercial account control and strict management [89]. Currently, global capital investment in public and private transport is between US$1.4 trillion and US$2.1 trillion annually [50], but promoting a more sustainable low carbon pathway for transport will depend on how future capital is invested.

Developing countries face great mobility challenges. Rural areas are often extremely poorly connected to transport infrastructure, such that, in contrast to the situation in developed countries, the benefits of road construction can strongly outweigh the total costs (including environmental ones). The main challenge, however, is to develop a solution to the problems arising from the combination of urbanization and motorization. Integration of transport and land-use policy will be key to rising to this challenge [72].

As a process of change in terms of urbanization and motorization, electric vehicles have been a good option requiring infrastructure in charging stations, whose implementation cost depends on the type of charging system. In the cities of United States, the estimated cost per unit from Level 1 alternating current is US$300 to US$1,500; Level 2 alternating current is US$400 to US$6,500; and the cost of direct current fast charging is US$10,000 to US$40,000 [77].

Investing in sustainable transport infrastructure is something national and local leaders want as a way to cut climate-warming emissions [97]. The construction of an electrified railway requires auxiliary infrastructure that, in addition to trains, can provide resources such as energy, telecommunications and internet access to regions that previously did not have promoting local development as a co-benefit. If the railway network in Brazil is electrified, it will also promote local development [13]. The costs of inhibition of land use and road infrastructure are shown in Table 5.

5.5 System Operations and Management

The System operations and management aim to improve travel efficiency through operational changes that avoid stops and fuel waste, keeping vehicles moving at moderate and efficient speeds and disseminating information to help train drivers using driving techniques more efficient [33].

An example of an operating system is the automatic vehicle location and real-time information system, which is a telematics system that offers opportunities to make urban transport more efficient, reducing the waiting time for pedestrians and cyclists from the reduction of the average time of operation of a traffic light, resulting in an increase in traffic flow and a reduction in traffic density [7].

As examples of operating system costs, we can mention the Adaptive Signal Control Technology Systems (ASCATS) adopted in the city of Detroit, United States, through the use of the system at intersections through faster and safer trips through

Table 5 Summary of costs of cases studies on land use and road infrastructure

Examples of measures	Case study	Characteristics	Costs analysis	Estimated costs ($)	References
Low emission zone (LEZ)	Cities of Scotland	Focus of a hypothetical Glasgow LEZ	Low-Medium–High	Capital cost US$2.792 million- US$21.899 million (2017)	Kay et al. [46]
Streets with restricted traffic-Bicycle Boulevards	Cities at Portland	The costs per section vary according to the length of the roads 1.2 mile to 4 mile and characteristics of the infrastructure works	Low	Cost of implementation US$31,135/km - US$89,238/km	Weigand et al. [100]
Implementation of electric vehicle charging stations	Cities (United States)	Costs associated with purchasing, installing, and owning non-residential charging stations	Low-Medium–High	Cost per unit from Level 1 alternating current US$300-US$1,500; Level 2 alternating current US$400–US$6,500; and cost of direct current fast charging US$10,000–US$40,000	Smith and Castellano [77]

Table 6 Summary of costs system operations and management technology

Examples of measures	Case Study	Characteristics	Costs analysis	Estimated Costs ($)	References
ITS - Adaptive Signal Control Technology systems	United States	Models InSync, SCATS and ACS-Lite	Low	US$8,000–US$35,000 per intersection	ITS (2012)
	Detroit in Michigan	Applied in intersections through Faster and Safer Travel through Traffic Routing and Advanced		US$28,800 per mile year	ITS (2010)

traffic routing and advanced, whose cost of execution is estimated at US$28,800 per mile per year. Other cases, such as the InSync, SCATS and ACS-Lite models the cost of ASCATS range from US$8,000 to US$35,000 per intersection [42, 43]. The costs of system operations and management technology are shown in Table 6.

5.6 Vehicle Energy Efficiency and Fuel Switching

Vehicle energy efficiency and fuel switching aims to introduce cleaner and more efficient vehicles, as an example through alternative propulsion systems and fuels with low carbon intensity, such as biofuels [33]. To achieve these objectives, vehicle efficiency improvement programs help to improve fleet efficiency and promote the use of alternative fuels, such as establishing a biofuel share in the composition of diesel and electrification to reduce the amount of fossil fuels [17].

The cost associated with the participation of biofuel in the composition of diesel can be exemplified by the case studied in Coimbra, Portugal, which carried out a test with biofuels in the public transport fleet in the ex-post scenario, whose average cost of operation was US$0.727 per v.km (vehicle kilometer) for B30 biofuel (30% biofuel and 70% diesel), US$0.853 per v.km for B40 biofuel (40% biofuel and 60% diesel) and US$0.85 per v.km for B50 biofuel (50% biofuel and 50% diesel) [14].

Green energy and transportation would save US$621 billion. The transition to total decarbonization in these specific sectors can bring additional benefits, such as 7.7 million new permanent jobs and 28 million temporary jobs. The Latin America and Caribbean region could have an annual savings of US$621 billion by 2050 if the energy and transport sectors achieve zero net emissions (including sea and land transport), in 2050 the region could reduce 1.1 billion tons of CO_2 equivalent.

The conversion to a fully renewable system would be the least costly way to electrify the region and achieve the objectives of the Paris Agreement. A renewable matrix will require a cumulative investment of US$800 billion dollars by 2050, less than a trillion dollars needed to meet the projected energy demand in the current commercial scenario, according to the study [34].

In addition to the use of alternative fuels, there is an enormous potential for electric vehicles (EVs) to reduce pollutants and CO_2 emissions in countries with an energy matrix composed mostly of clean sources (e.g.: Brazil). Despite having a lower operating cost, EVs still have a higher total cost than internal combustion vehicles. EVs are identified as a fundamental part of the ongoing transformation in the electricity sector with the potential to optimize the use of intermittent renewable energy sources.

However, for the benefits of extensive transport electrification to be real, the electrical energy that feeds them must come from clean energy sources and renewable [53]. In Developing Countries rechargeable EVs are expensive, low operational autonomy and need for loading infrastructure, being its dissemination still small today. Vehicles with a high degree of use, such as taxis, mobility-as-service and freight vehicles, may be more suitable from the economic point of view for electrification [1, 53].

Use of BEV, electric vehicles for hydrogen fuel cells (FCEV) and plug-in hybrid vehicles for hydrogen fuel cells (FCHEV) assist in improving the road transport system with powertrain life cycle costs estimated in 2030 of US$6,460 to US$11,420 to BEVs, US$7,360 to US$22,580 to FCEV, and US$4,310 to US$12,540 to FCHEVs [63].

Within shared mobility, two elements will support the development of EVs: (i) the emergence of transport service operators (e.g., car sharing and travel sharing companies); and (ii) intermodally systems (mobility as a service). Car sharing and travel sharing companies eliminate travel costs purchase, possession and maintenance of vehicles for users. Furthermore, they provide cost-effective for the adoption of EVs due to the high degree of vehicle utilization (costs lower than Internal Combustion Engine Vehicles -ICEVs). According to the World Economic Forum [103], electrified fleets of taxis, commercial vehicles and public transport should be the focus of e-mobility in the future, as they will have a greater impact than private vehicles due to the fact that they represent the largest volume of miles traveled in cities.

As a primary strategy for public transportation the use of electric buses represents an important link to meet the need for sustainable urban transport, however they need an efficient, accessible and quality transport network to attract customers and induce the migration of the individual transport user for the public transport network, combining a significant impact on air quality and on the quality of life and health of citizens [83]. Electric buses generally have lower operating costs than traditional buses due to savings from reduced fuel consumption and lower maintenance costs [12].

The option of electric buses eliminates the transmission, clutch and combustion engine. With far fewer parts and a simpler design, maintenance costs are also lower, depreciation slower; longer service life, as well as residual value. The assessment of indirect gains is more complex than a fuel substitution. The conclusion is that, even if the electric bus costs twice as much as the conventional diesel bus, the economic benefits would justify the change [47]. One of the ways to encourage the use of electric buses is exemplified by Project Transport electrification in Europe, which invests in the development of a retrofit system for battery and recharger of the fully electric drive system for an 18-ton bus and capable of traveling 160 km, with a total cost of US$ 2,728.60 directed to the project.

Sheth and Sarkar [74] has explored the life cycle costs involved in the procurement and operation of electric buses as opposed to diesel buses through Total Cost of Ownership (TCO) calculations and Net present value (NPV) analysis, where the external cost of environmental pollution was calculated separated. According to the analysis, it was observed that when evaluated over a life cycle of 25 years, which is the normal life of transport infrastructure such as pavements in India, the TCO for electric buses (INR 36.6 million, or US$ 571,875) is significantly lower than that of diesel buses (INR 39.1 million, or US$ 610,938) even if the external costs of pollution are ignored.

The migration of mopeds and motorcycles to EVs technology is also part of the solution to the challenges of sustainable urban transport, as they meet the needs of door-to-door travel and short trips that are not suitable for fixed route traffic systems with very low emissions, as they represent almost 30% of the total motorized vehicles worldwide, varying between 50 and 90% in cities in developing countries [28].

Electric-powered modes, such as LRT, HRT, and electric-trolleybus-powered BRT, can be cheaper to power in countries with a plentiful, stable and low-cost electricity supply (such as those with ample hydroelectric power) than in countries with high cost, unstable electricity supplies. BRT systems can also introduce new buses that use hybrid-electric technology, CNG, LPG, ethanol blends, hydrogen fuel cells, or other alternative fuels [40]. The costs of vehicle energy efficiency and fuel switching are shown in Table 7.

5.7 Synthesis of Results

It is noted that certain mitigation actions are more limited than others to achieve sustainable transport. For example, the construction of walking and cycling infrastructures has a low implementation cost, while the implementation of BRT lines has a high implementation cost.

However, it is also emphasized that mitigation actions, even the most expensive ones, can fit better in the region under study. For example, areas with limited road space may present the implementation of a metro as a more attractive option. Therefore, it is important that the transport decision makers carry out an in-depth study of each of them in order to choose the best option available.

Table 7 Summary of cost of vehicle energy efficiency and fuel switching

Examples of measures	Case Study	Characteristics	Costs analysis	Estimated Costs ($)	References
Retrofit all-Electric Bus	Project Transport electrification in Europe	Development of a retrofit all-electric drive system, battery, and recharger pack for bus	Medium	Total project cost US$2.729 million	European Comission (2020)
Use of biofuel type B30; B40 and B50	Coimbra (Portugal)	Testing Biofuel	Low	Average operating costs of B30—US$ 0.727/v.km; B40—US$ 0.853/v.km and B50—US$ 0.85/v.km	CIVITAS (2014)
Alternatives vehicles	Road transport system	Use of battery electric vehicles; electric vehicles for hydrogen fuel cells and plug-in hybrid vehicles for hydrogen fuel cells in road transportation	Hight	The powertrain lifecycle cost estimated to 2030 of FCEVs—US$7,360 to US$ 22,580; BEVs—US$ 6,460 to US$ 11,420; and FCHEVs—US$ 4,310 to US$ 12,540	Offer et al. [63]

6 Conclusions and Recommendations

The Paris Agreement under the NDCs presented by Countries and the SDGs set ambitious targets for sustainable progress. Road transportation plays a particularly important role in meeting these targets, given that a significant portion of the global GHG related to energy comes from this sector. In addition, excessive consumption of natural resources leads to depletion. A review of the transport mitigation actions listed in NDCs from developing and emerging countries showed that the distribution of mitigation actions has a strong focus on fuels and vehicles, and recognized the urgency to promote a low carbon transport in the urban transport infrastructure such as road.

Thus, this study sought to present actions to mitigate the impacts of road transportation, regarding GHG emissions and the natural resource depletion. In addition, it was possible identify that the cost to shifting to road sustainable transport is a gap in literature and it is necessary an investment new researches and identification of finance opportunities to help decisions makers to prioritize actions according their capabilities and considering the best options for each city.

We sought to highlight the cost necessary of shifting to sustainable transport, and the results of the literature review indicate that any mitigation action implemented to promote a low carbon transition in road transportation must maximize synergies between the SDGs and their targets, especially those related to clean energy and climate action. Active transportation is emerging as great solutions for urban transportation in cities, especially during the pandemic due COVID-19 and the necessity of social distancing, with options as bike sharing systems, and infrastructure for walking, with estimated costs for projects variating from low-medium cost. However, it is important to consider all low carbon measures, including high investments as example Metro, LRT and BRT with fleet of battery-electric articulated buses to move toward sustainability in cities.

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Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario

Meenu Gautam and Madhoolika Agrawal

Abstract Increases in the population and prosperity are significant contributors to waste generation. Globally, ~2.01 billion metric tonnes of municipal solid waste (MSW) are produced annually, which are expected to upsurge by two folds in 2050, thereby raising a matter of concern in future. The chapter aims to assess the greenhouse gas (GHG) emissions from MSW management and its subsequent impacts on socioeconomic status of people and ecological systems. The study also includes mitigation strategies to reduce emissions of GHGs from waste management. The life cycle assessment of MSW management in relation to GHG emissions discloses that more than 50% of the collected waste is not managed properly instead openly burned or dumped at landfills in most developing countries. Moreover, nearly 10–40% is processed through recycling and composting. Total GHG (CH_4, CO_2, and N_2O) emissions from waste management contribute approximately 5% of overall GHG emissions into the atmosphere. Methane generation exclusively accounts for 1–2% of GHG release from the process of waste management. The emitted GHGs lead to global warming, climate change, and adversely affect the living organisms on the earth. Therefore, sustainable management of the system from collection to treatment and disposal with special emphasis on GHGs emission minimization is essential to sustain the available resources and safeguard the environment. The study highlights the strategies such as 5-R principal, waste segregation at household level, use of natural gas-based vehicles, advanced modifications in the system of waste management in developing countries, utilization of compost and residue as manure, and reclamation of abandoned landfill sites to mitigate the emissions for sustainable progression of the nations. The review also provides a basis for decision-makers in local, national, and regional levels to formulate and execute strategies and policies for mitigating GHG emanations during MSW management.

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Keywords GHGs · Global · Life cycle assessment · Methane · Municipal solid waste management · Mitigation

1 Introduction

Solid waste refers to any unwanted solid materials of everyday use that are generated by community activities. Of the total solid waste generated worldwide, ~70% constitute municipal solid waste (MSW) [78]. Increase in population and prosperity are the two critical drivers for waste generation, thereby making MSW management one of the key challenges of the twenty-first century [22]. Globally around 2.01 billion tonnes (Bt) of MSW are generated annually, of which East Asia and Pacific stands at the top (23%) followed by Europe and Central Asia (20%), and South Asian countries (17%) in terms of MSW generation (Fig. 1a) [78].

Worldwide waste generation per person per day averages 0.74 kg and ranges widely from 0.11 to 4.54 kg [78]. Waste generation, however, depends on several factors such as population, development, and income level of the nation, etc. There is generally a positive correlation between waste generation and income level (Fig. 1b). High-income countries generate about 683 million tonnes (Mt) of MSW [78]. Since, all the countries want to progress in all the possible ways to provide quality of life to their citizen; there are increases in industrialization, urbanization, and commercialization with simultaneous increase in population. Thus, when looking forward, the MSW generation has been projected to increase to 3.40 Bt by the end of 2050 [78]. The fastest-growing regions will be the Middle East as well as North Africa, South Asia, and Sub-Saharan Africa where total waste generation is expected to increase by 2, 2, and 3 folds, respectively by 2050.

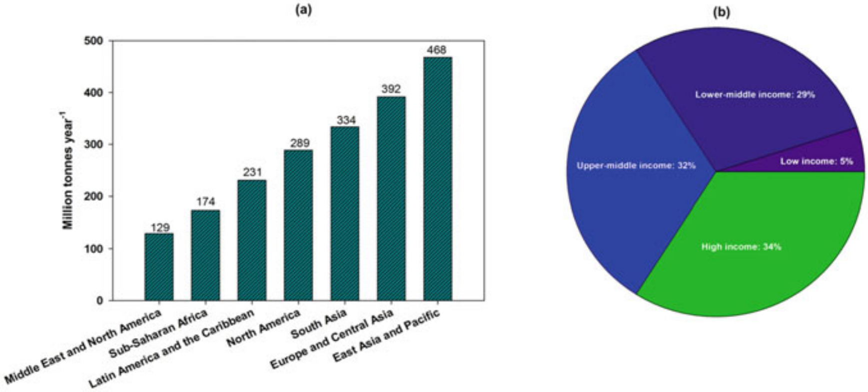

Fig. 1 Amount of municipal solid wastes generated from different regions of the world (**a**) and percentage contribution in waste generation based on the global economy (**b**) (based on the data from [78]

Composition of generated MSW can be categorized into organic and inorganic. Organic fraction of the waste mainly includes food wastes (mixed), plant materials, paper and cardboard, textile and gunny bags, animals' wastes and decomposed garbage, etc. (Table 1, Fig. 2) [34]. Whereas, inorganic fraction of MSW encapsulates construction wastes, plastics, glass, metals, rubber, thermacole, electronic wastes (e-waste), multilaminates, ashes, and other processed trashes having inorganic constituents (Table 1, Fig. 2). Percentage contribution of both organic and inorganic fractions in MSW generated from different areas of the world is illustrated in Table 2 [44]. Composition of MSW is greatly influenced by geographical loca-

Tables 1 Sources of organic and inorganic constituents in municipal solid waste

Type	Sources
Organic	Food material, garden trimmings, branches, grass cuttings, raw peelings, bagasse, organic residues, animal excreta, decomposed garbage. residues from slaughterhouses, etc.
Paper and cardboard	Cardboard, newspapers, wrapping paper, paper scraps, telephone books, magazines, bags, boxes, shredded paper, paper disposables
Plastics	Bottles, containers, packaging, bags, toys and lids, etc.
Glass	Bottles, light bulbs, broken glassware, cultured glass, etc.
Metals	Container, foil, tin, nonhazardous aerosol can, appliances, railing, vehicle, and other utilities
Others	Leather, textiles, multilaminates, rubber, e-waste, building and construction waste; appliances, ash, and other inert materials

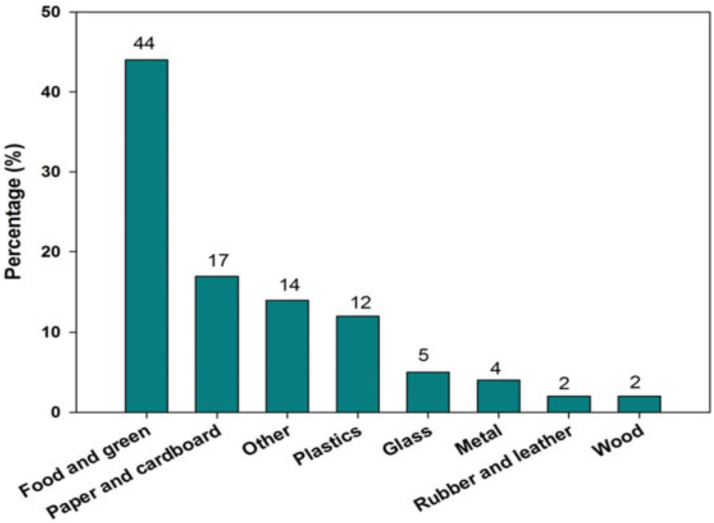

Fig. 2 Percentage of food and green, paper and cardboard, plastics, glass, metal, rubber and leather, wood, and miscellaneous constituents in MSW worldwide (based on the data from [34]

Table 2 Percentage contribution (%) of food, garden, paper and cardboard, wood textile, nappies, rubber and leather, plastic, metal, glass, and other miscellaneous materials (mean value) in municipal solid waste from collection to disposal at landfill sites across different regions of the world

Region	Food waste	Garden waste	Paper and cardboard	Wood	Textiles	Nappies	Rubber and leather	Plastics	Metals	Glass	Other
Asia											
Central	30.0	1.4	24.7	2.5	3.5	0	0	8.4	0.8	5.9	23.0
Eastern	40.3	0	20.4	2.1	1.0	0	0	6.5	2.7	4.3	22.9
South-Eastern	49.9	1.0	11.2	0.8	0.4	0	0	10.2	4.2	3.7	18.6
Southern	66.1	0	9.2	0	1.2	0	0.4	7.0	0.9	1.5	13.9
Western	42.2	3.2	15.3	0.8	3.0	0.4	0.3	17.2	2.5	3.4	11.8
Africa											
Northern	50.4	0	12.1	0	5.8	0	0	13.8	4.4	3.3	10.5
Eastern	44.4	6.9	10.4	0.5	3.0	0	0.4	8.0	2.6	2.1	21.7
Middle	28.4	0	8	0	1.3	0	0	7.1	1.4	1.1	52.7
Southern	24	0	14.5	0	5.5	0	0	26.5	6.5	9.0	14.0
Western	53.9	0	7.5	0	1.9	0	0	6.4	2.7	1.3	26.5
Europe											

(continued)

Table 2 (continued)

Region	Food waste	Garden waste	Paper and cardboard	Wood	Textiles	Nappies	Rubber and leather	Plastics	Metals	Glass	Other
Eastern	31.8	2.4	17.1	2.5	3.1	0.1	0.5	4.6	0.7	1.8	35.3
Northern	30.3	5.2	13.8	1.8	3.2	1.2	0	4.9	1.4	4.3	34
Southern	35.8	1.4	21.4	1.2	2.8	1.1	0.2	14.1	2.0	3.5	16.7
Western	33.2	2.7	17.2	2.3	5.9	3.0	0	20.5	1.5	1.4	12.3
America											
Central	62.7	0	12.6	0.3	2.2	0	0	10.3	2.7	3.3	6
Southern	54.1	3.3	12.4	0	1.7	1.9	0.6	13.7	2.0	3.0	7.2
North	20.2	6.8	23.3	4.1	3.9	0	1.6	15.8	6.4	4.2	14.0
Australia and New Zealand	25.9	12.2	12.0	6.5	2.9	3.5	0	8.3	1.8	2.8	24.1

Source: IPCC [45]

tion, cultural norms, economic development, energy sources, and climatic conditions [34]. High-income nations have higher consumption of inorganic supplies (such as plastics, laminated paper, glass, and metals); hence have high generation of inorganic/recyclable waste. While, low to middle income countries have high organic fraction in MSW, i.e., 40–85% compared with 28% in high-income countries [34].

Climate of the region also influences the composition of the wastes [34]. Precipitation and humidity play crucial role in waste composition, particularly when measured by mass because of absorption of moisture from the atmosphere [34]. Waste of dry region has low moisture content and vice versa. For an instance, [68] showed that in Muscat, Sultanate of Oman, 33.6% by weight and 16.7% by volume of MSW were generated in winter, and 22.8% by weight and 7.8% by volume in summer. Physical properties of MSW show density, volatile solid, ash, and moisture content in the range of 65–480 kg/m^3, 69–86%, 0–68%, and 2–91%, respectively (Table 3). Chemical properties such as electrical conductivity, pH, contents of carbon, oxygen, hydrogen, sulfur, chlorine, organic carbon, organic nitrogen, phosphorous and potassium, C/N ratio, fixed residue, and calorific value of MSW from different countries are presented in Table 3. Chemical composition of MSW in West Bengal exhibited high moisture, ash, and inorganic contents, while contents of nitrogen, phosphorus, and potassium were relatively low [74].

Tremendous generation of MSW has creating and likely to create a massive problem in upcoming future. Improper management of MSW has severe negative consequences on the environment as well as human health [75]. The disintegration of waste into harmful chemical constituents is a common source of environmental pollution and is severe mainly in developing nations. Severe negative consequences of MSW disposal were described in various cities of different countries such as China [10], India [80], Malaysia [51], and Thailand [11]. Poor management of MSW has become an inevitable challenge for governments of many Asian and African countries [24].

Management of MSW generally involves segregation at source point, door-to-door collection, transportation, storage, segregation at storage house into biodegradable and nondegradable wastes (plastics, metals and glass), material recycling, anaerobic digestion and composting of organic wastes, incineration/thermal treatment for waste-to-energy recovery and finally the residues are disposed at landfill sites. However, the above-mentioned sequence of waste management varies with countries, states, and cities. Figure 3 shows percentage contribution of various treatment processes in waste management globally [34]. Furthermore, Fig. 4 depicts the MSW treatment contribution by various countries across the world. In developed countries, wastes management is strictly complied with the norms, regulations, and policies of IPCC and EPA. While, the developing countries like China, India, South Africa, Nepal, Pakistan and Bangladesh, etc., are yet to be in strict alignment with the IPCC and EPA protocols. In these regions, currently more than 50% of the waste is openly dumped and the waste growth curves are likely to have vast insinuations for the environment, health, and prosperity, which necessitate a quick call for appropriate and urgent actions.

Tables 3 Physicochemical properties of municipal solid waste from collection to disposal at landfill sites

Properties	Range	References
Moisture content (%)	2–93	[36]1; [73]2; [74]3; [6]4; [21]5; [53]6; [29]7;
Volatile matter (%)	2–83.32	[36]1; [82]8; [53]6; [102]9; [87]10
Ash content (%)	1–76.8	[59]15; [36]1; [74]3; [102]9
Density (kg m^{-3})	65–480	[74]3
pH	4.4–8.12	[73]2; [74]3; [82]8; [21]5
Electrical conductivity (dS m^{-1})	0.19–0.29	[82]8
Carbon content (g kg^{-1})	21–64.32	[36]1; [74]3; [102]9
Nitrogen content (g kg^{-1})	0.96–5.11	[36]1; [74]3; [102]9; [87]10; [52]11
C/N ratio	13.0–30.94	[18]12; [73]2; [65]13; [71]14
Hydrogen content (g kg^{-1})	0.1–9.2	[36]1; [74]3; [102]9
Oxygen content (g kg^{-1})	0.07–44.24	[36]1; [74]3; [87]10
Sulfur content (g kg^{-1})	0.05–5	[36]1; [74]3; [52]11
Organic carbon (%)	0–27.6	[74]3
Organic nitrogen (%)	0.34–0.70	[74]3
Phosphorous (P_2O_5) (%)	0–0.82	[74]3; [65]13; [52]11
Potassium (K_2O) (%)	0–0.83	[74]3; [65]13; [52]11
Calcium (CaO) (g kg^{-1})	0–14.9	[18]12
Magnesium (MgO) (g kg^{-1})	0–3.33	[18]12
Chlorine content (%)	0.39–2.48	[6]4; [102]9
Fixed residue (%)	3.2–87.13	[74]3; [102]9
Calorific value (kcal kg^{-1})	900.61–4568.7	[6]4; [65]13; [87]10

1: South Africa; 2: Iran; 3: Bangladesh; 4: Turkey; 5: Germany; 6: The USA; 7: Island of Crete, Greece; 8: Mauritius; 9 and 15: China; 10: Thailand; 11: Africa; 12: Spain; 13: India; 14: Pakistan

Greenhouse gas (GHG) emission from various anthropogenic sources is an important global issue considering the environmental health. Per capita annual carbon dioxide (CO_2) emission increased from 2.2 tonnes (t) in 1990 to 7.5 t in 2014, with a growth rate far higher than the world's average per capita level [44]. China followed by the USA and India are the largest contributors of GHG emissions (Fig. 5) (44]. According to [96], waste is the largest research area of focus for emission followed by energy reduction in the world. It is expected that waste sector including solid and wastewater treatment contributes 3–4% to the global anthropogenic GHG emissions [25]. Municipal solid waste sector is the fourth largest contributor to global GHG emissions accountable for approximately 5% of the global greenhouse budget [39]. This 5% consists of methane (CH_4), carbon dioxide (CO_2), nitric oxide (N_2O), and fluorinated gases (such as perfluorocarbons (PFCs), hydrofluorocarbons

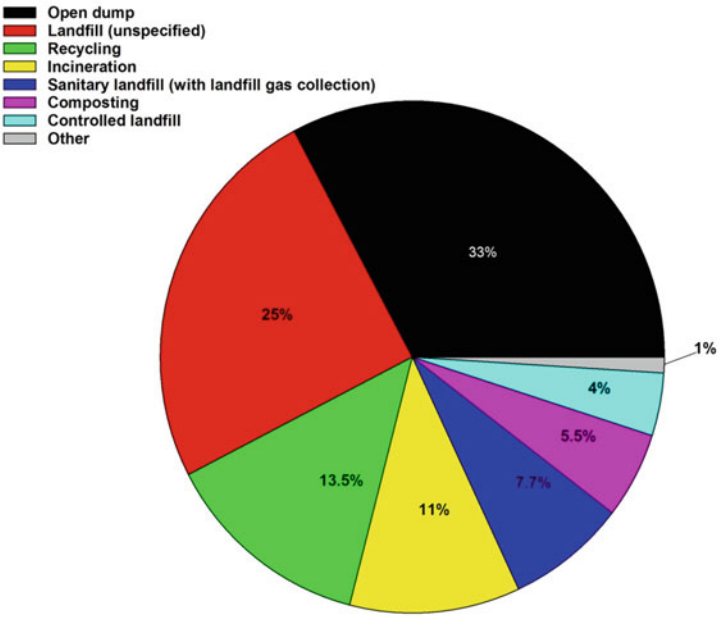

Fig. 3 Various treatment processes and their percentage contribution in municipal solid waste management globally (based on the data from [34])

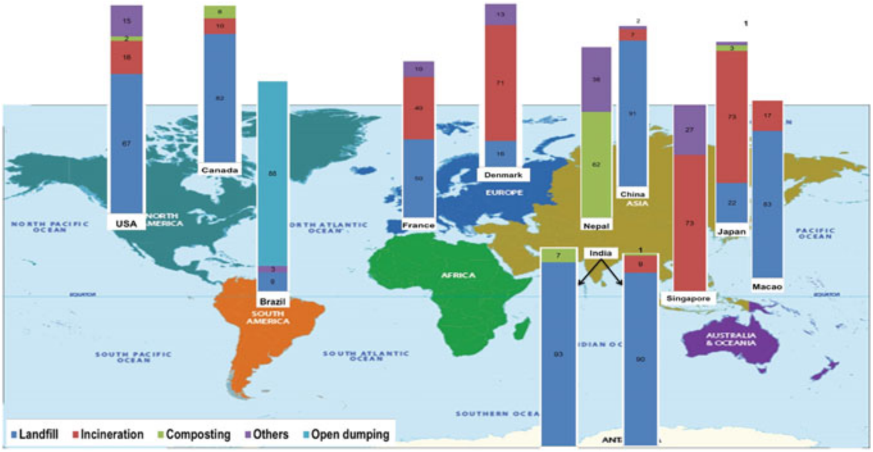

Fig. 4 Percentage contribution of various treatment processes (composting, incineration, open dumping, landfill, and other miscellaneous processes) in management of municipal solid waste in different regions of the world (Modified from [98])

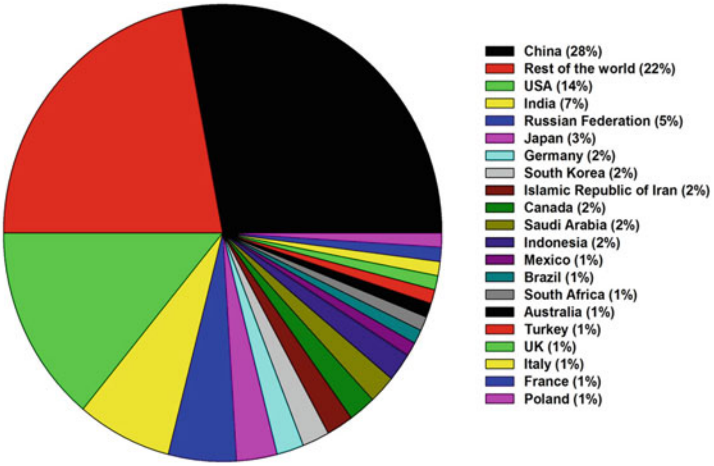

Fig. 5 Percentage contribution of different countries in greenhouse gas emissions from municipal solid waste management (adapted from [44])

(HFCs), chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3)). Moreover, CH_4, CO_2, and N_2O are dominant GHGs from waste sector [92].

Municipal solid waste releases a gaseous mixture predominantly of CH_4, CO_2, and N_2O generated by microbial decomposition of carbon as well as nitrogen-containing compounds and combustion along the hierarchy of waste management (waste generation, storage in bins, collection, transportation, disposal, recycling, composting/incineration, and final disposal at landfill sites). Composting, incineration, and landfills are the chief sources of atmospheric emissions (CH_4, CO_2, volatile organic compounds, noxious gases and fumes, etc.). Manfredi et al. [60] stated that mixed wastes are solely responsible for direct emissions of GHG up to 300 kg CO_2e t^{-1}. Its contribution to GHG emissions reaches ~3% worldwide and up to 15% in developing economies [4]. Thus, the appropriate selection of waste processing techniques via integrated waste management system having negligible emissions and consequent impacts is imperative.

The chapter thus aims to describe the emission scenario of greenhouse gases from varying processes involved in municipal solid waste management through life cycle assessment approach and the subsequent impacts on socioeconomic and ecological systems. The study also includes the mitigation steps for sustainable management of municipal solid waste to reduce greenhouse gas emissions.

2 Literature Search

Worldwide datasets on MSW generation, waste composition, and greenhouse gas productions during waste management system were collected from peer-reviewed literatures available at the Web of Science (accessed till the end of July 26, 2020), official sites of World Bank, IPCC, EPA, IEA [46, 47], NASA, NOAA and national monitoring web networks of USA, China, and India. Published papers from 2001 to 2020 were considered for the global MSW generations' and GHG emissions' scenario. Data from table, text, and figures were extracted for the accomplishment of this review study. Specific keywords such as MSW, life cycle assessment, landfills, GHGs, CH_4, CO_2, N_2O, effects of GHGs, and mitigation strategies were used to access the search engines and other web networks.

3 Methodologies for the Estimation of GHG Emission

The inventory by the IPCC enlists various calculation methods for the emissions of GHGs from waste disposal [39, 40]. The IPCC describes four main types of GHGs accounting such as national accounting, corporate-level accounting, life cycle assessment, and carbon trading methodologies [25]. Many academics have followed the IPCC guidelines in calculating GHG emissions from MSW management [39, 40]. Carbon factor used in calculation varies with the type of vehicles and treatment procedures, and the factors used in GHG computation are derived from the Waste and Resources Assessment Tool (WRATE) version 2 and the Department of Energy and Climate Change data [30]. To study the GHG emissions from landfill sites, LandGEM modeling is widely used [9].

Existing literature on quantification of GHGs during MSW management in both developed and developing nations were surveyed with a particular focus on the life cycle assessment [9, 16, 61]. Figure 6 shows generalized framework in estimating GHG emanations from MSW management for both developing and developed nations. However, huge differences in quantitative estimation of GHG emissions between developed and developing nations are because of lack of resources, information, mandatory obligations, and expertise [92]. Overall assessment of GHG releases through the entire management system of MSW, i.e., collection, transportation, storage, intermediate facilities (material recovery, composting, incineration and/or thermal treatment), and landfill sites are analyzed using GHG calculator. The GHG calculator is an Excel-based tool to estimate GHG emissions [30]. It measures CH_4, CO_2, and N_2O emissions, expressing them as CO_2e emissions or savings, depending upon how the waste is managed [30]. There are different carbon modules in the GHG calculator; each contains information about the CO_2e performance of each waste management system.

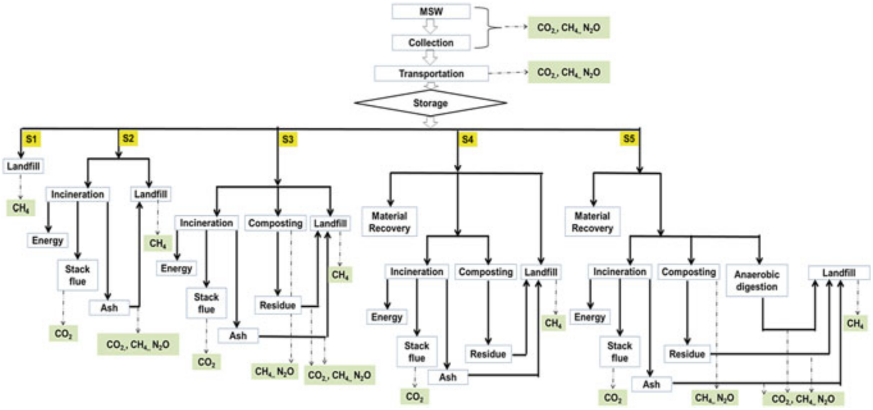

Fig. 6 Scenarios in life cycle assessment of municipal solid waste management (from collection to landfill wastes) with respect to major greenhouse gas emissions (CO_2, CH_4, and N_2O). CO_2: carbon dioxide; CH_4: methane; N_2O: nitric oxide; S1: scenario 1; S: scenario 2; S3: scenario 3; S4: scenario 4; S5: scenario 5

4 Life Cycle Assessment of MSW Management

Life cycle assessment (LCA) is a science-based cumulative approach to enumerate the impact of the entire system, process, or product on the environment [12]. It is the computer-aided tool that is increasingly used for sustainable management of MSW since 1995, specifically in decision-making and adoption of management strategies [32]. LCA is ideal in MSW management because of wide variations in geographical location, properties of the wastes, energy resource, limited availability of disposal sites, market size of the product resulting from the wastes, and in reducing local pressure and waste management cost [62]. Cumulatively, LCA is essential to evaluate, identify the hotspots, and diagnose the possible improvements on reducing and controlling the environmental impacts of GHG emissions along the waste treatment hierarchy. Based on International Organization for Standardization (ISO) 14040 and 14044 [48, 49] and International Reference Life Cycle Data System (ILCD) Handbook [23], LCA has following four sections.

4.1 Goal and Scope Definition

It is the first stage in the LCA of MSW management [48]. The scope and goal may vary from general (e.g., testing the validity of the “hierarchy of waste”) to specific (e.g., comparing the environmental performances of several possible designs for a MSW management system in particular community) assertions. Many studies have been conducted based on different goals and scopes of MSW management. These include identification of options for minimizing the adverse environmental impact, energy consumption, and economic costs; to reveal the plausibility and limitations of economic information in MSW management; to bring out the comparative assertions in regulation of MSW management and to evaluate the compatibility of LCA with the hierarchy of MSW management [12]. The present study, however, infuses the LCA of MSW management with GHG emissions from cradle to grave for clear understanding of gaseous emissions (Fig. 6).

4.2 Functional Unit and System Boundaries

Functional unit is a well-defined and measurable phase [48]. It provides a basis to understand and compare the results of LCA at general and specific levels [48]. While a system boundary defines the unit processes, i.e., stages, inputs as well as outputs within the system. It comprises the total elements of the system upon which the computations of impacts are based. The LCA of MSW management system ensures the GHG emissions out of the inputs at various stages of management systems (Fig. 6). In addition, both are allied to the generation of useful products such as compost, heat and electricity. More specifically, it includes management of one tonne of MSW with specific composition over a definite period of time to compare the alternative scenarios [94]. Functional unit and system boundaries are comprised of following five scenarios for clear illustration of baseline to advanced management processes.

4.2.1 Scenario 1

It is a baseline scenario for developed and developing nations, where maximum proportion of MSW after collection is dumped to landfill sites having no provision for leachate and gaseous collection. Landfill sites at baseline scenario may or may not have gas flares. Thus, there is more harmful impact of scenario 1 on the environment because of maximum releases of GHGs (CH_4) from the landfill sites (Fig. 6).

4.2.2 Scenario 2

Incineration or thermal treatment facilities equipped with baseline scenario led to recovery of energy from MSW with subsequent generation of flue gas and ash. Relatively less proportion of waste is generally utilized for energy recovery due to high waste generation and less capacity of the incinerator [72]. In this scenario also maximum proportion of MSW is disposed without proper pretreatment to landfills, which consequently leads to high GHG emissions (Fig. 6).

4.2.3 Scenario 3

Composting and incineration units are facilitated with scenario 2, which carries out segregation of wastes into inorganic and organic followed by aerobic digestion of biodegradable fraction and recovery of energy from nonbiodegradable. The outputs of the scenario are GHGs, flue gas, compost, and residues from incinerator (Fig. 6). The scenario minimizes the waste generation to landfill and GHG emissions compared with scenario 2.

4.2.4 Scenario 4

Scenario 4 supports the material recycling of waste along with composting and incineration. Material recycling unit reduces the amount of the wastes to a significant level through the recovery of reusable plastics, glass, and metals. Recovery of recycling materials followed by composting of biodegradable waste and incineration of remaining waste leads to disposal of the relatively less fraction of MSW (compost and residues from incineration) at the landfill (Fig. 6). In this case, emitted CH_4 is harnessed for energy recovery and thus reduces landfill GHG emissions.

4.2.5 Scenario 5

This is the progressive scenario widely practiced in developed countries and in some cities of developing countries to manage MSW. The scenario is the combination of previous four scenarios where after collection, transportation and recycling of materials, equal proportions of biodegradable waste are subjected to anaerobic digestion and composting followed by incineration and waste disposal at landfill sites (Fig. 6). Intermediate treatment processes from collection to disposal site reduce the GHG emissions and landfill waste to a great extent. Landfills are further inculcated with more advanced system of methane collection and energy generation units.

4.3 Life Cycle Inventories (LCI)

System boundaries are further divided into foreground and background systems [5]. Foreground system is allied to the generation of useful products such as electricity and compost along with simultaneous emissions to air (e.g. GHG emissions), water and soil during material recycling, composting, anaerobic digestion, and disposal at landfill. Background system incorporates the utilization of resources (MSW, energy, storage containers, and vehicles) to the foreground system [5]. These inputs and outputs are quantified and qualified during LCI of the various processes involved in MSW management. Collection of MSW can either be in mixed or segregated forms. However, wastes in segregated form from point source are highly encouraged as it leads to successful material recovery. There are certain parameters such as selective collection system, storage containers (made of High Density Polyethylene (HDPE), fiberglass, and steel materials), collection frequency, distance covered, type of collection truck (pneumatic, top, rear, and side loader), fuel of collection truck (diesel and natural gas), density and fraction of wastes, size, and filling percentage of container influence the collection and storage of MSW and thereby affecting the LCI.

4.4 Life Cycle Impact Assessment (LCIA) and Sensitivity Analysis

This is the evaluation of the environmental burden and benefits. It is primarily based on following six impact categories, i.e., global warming (kg CO_2 (eq) t^{-1}), abiotic depletion (MJ), acidification (kg SO_2 (eq) t^{-1}), nutrient enrichment (kg PO_4 (eq) t^{-1}), photochemical ozone creation (kg C_2H_4 (eq) t^{-1}), and human toxicity potentials (DCB (eq)).

4.5 Life Cycle Interpretation (LCIP)

LCA in MSW management is a challenging task because its management facilities require large land area, consume nonrenewable resources (electricity and fuels), and emit pollutants as well as leachates. On other hand, MSW management generates useful products such as reclaimed plastic, paper and cardboard, glass, compost as fertilizer and thermal treatment of wastes produces heat and electricity. Besides, landfilling that is the most widely used method for the management of MSW in most of the countries has a lot of uncertainties related to time frame of the impact. Thus, waste management system itself puts enormous pressure on natural environment. Therefore, there are certain approaches to amplify the LCA approach to manage MSW and GHG releases from the system UNEP [89]:

- Reconsidering the product and analyses the functional unit in detail
- Reducing the consumption of raw material and energy
- Replacing the traditional consumables with less harmful raw materials and energy-efficient production methods
- Recycling of materials
- Repair and redesigning products for reuse.

5 Greenhouse Gas Emissions from MSW Management System

Greenhouse gases are the prime cause of global warming and climatic change, which are subsequently affect the ecological balance and cause abiotic resource depletion, etc. [55]. Global warming is the result of increasing temperature due to emissions of GHGs such as CO_2, CH_4, and N_2O. The LCA of MSW management clearly exemplifies the points of emission of major GHGs such as CH_4, CO_2, and N_2O (Fig. 6). Thus, waste collection, transportation, anaerobic digestion, composting, incineration, and landfill contribute significantly to GHG emissions during waste management process.

5.1 GHG Emissions from Waste Collection and Transport Systems

Greenhouse gases (mainly CO_2 and small amounts N_2O and CH_4) are released in the process of waste collection and transportation due to combustion of fuel. Collection rates have been much lower in developing nations as compared with their developed counterparts. For instance, Organisation for Economic Co-operation and Development (OECD) countries have collection rates varying from 90 to 100%, while developing countries have comparatively low collection rates [67]. Lower collection rates however cause less GHG emissions and vice versa because aerobic digestion of uncollected waste may lead to no CH_4 generation, rather CO_2 is emitted [5, 95]. In developing countries, methods adopted for the collection of waste might not be technologically advanced are causing less GHG emissions. In many African and Asian countries, manpower is employed in waste collection such as wheelbarrows, animal-drawn carts, pedal tricycles and push carts, etc., which are not fuel-based vehicles and thus result in no GHGs emission [8, 37]. For developed countries, GHG emissions ranged between 5 and 50 kg $CO_2e\ t^{-1}$ of wet waste [19].

In European nations, on an average 7.2 kg $CO_2e\ t^{-1}$ of waste was produced during MSW collection and transportation [81]. In the UK transportation and waste segregation resulted in 14,234 and 13,323 t CO_2e of GHG emissions, respectively [16]. The GHG emission of waste in developing countries such as Saudi Arabia was nearly 24935 t CO_2e in Saudi Arabia [97]. Waste collection along with transportation in Taipei city of Taiwan accounted for 15.53 kg $CO_2e\ t^{-1}$ of waste [25]. The emissions from transportation of collected MSW to landfill in Beijing, China varied from 91.49 t CO_2e to 102.69 t CO_2e under the five scenarios of LCA, thereby accounting for 0.56–2.15% of GHG emissions during whole management process [96].

5.2 GHG Emissions from Waste Segregation and Material Recycling Facilities

Waste segregation and recycling replace the raw materials in production, reduce the cost incurred and energy consumption in production processes, and minimize the GHG emissions during further management processes [5]. The MSW is maximally contributed by organic wastes such as domestic and agricultural wastes, and recyclable materials as stated previously [34]. Organic wastes have high proportion of moisture content whose treatments consume more energy and thus there are more gaseous emissions. Similarly, in the process through recovery of recyclable materials such as glass, metals, and plastic, quality cascading occurs in many countries at large scale, which is energy consuming [96]. Nonetheless, most developed countries and some developing nations have implemented comprehensive recycling programs for recycling of materials in order to reduce the burden on MSW management. All these lead to indirect energy conservation and great reduction in GHG emissions. [81] thoroughly addressed the GHG emissions' benefits from recycling across the European Union (EU). Pimenteira et al. [69] quantified GHG emission reductions from recycling in Brazil. At Beijing in China, total GHG emanations from incineration were reduced by 0.0251 t CO_2e after sorting and recycling of MSW at material recycling facility [96].

5.3 GHG Emissions from Composting and Anaerobic Digestion

Several developed and developing nations practice anaerobic digestion and composting of mixed biodegradable waste fractions (kitchen, garden and agricultural wastes, etc.). Generally, composting is applicable to dried waste, while anaerobic digestion is more suited for wet waste [5]. Composting decomposes waste into CO_2, water, and compost with high humic acid content, whereas anaerobic digestion of waste in the absence of air leads to CH_4 generation. Composting is relatively cost-effective and sustainable approach in managing MSW in developing countries, and yields compost. Depending on compost quality and properties of soil, there are several probable applications for MSW compost in agriculture and horticulture to stabilize and improve soil quality [13]. Xin et al. [96] reported that compost is the fraction of MSW, which emits least GHGs and further reported that the GHG emissions t^{-1} of waste composting is only 0.177 t CO_2e in China. A study conducted by [61] in Queensway, UK found that GHG emissions from normal composting release 470 kg CO_2e t^{-1} of waste, while solid anaerobic digestion batch with inoculum and postcomposting reduce the generation to 382 kg CO_2e t^{-1} of waste. Kristanto and Koven [54] reported that GHG emissions from anaerobic digestion and composting resulted in net emissions of GHG of 40 and 340 t CO_2e day^{-1} in Depok, Indonesia.

5.4 GHG Emissions from Incineration and Thermal Treatments

Incineration or thermal treatment unit consists of a fuel chamber where fossil fuel such as natural gas/oil is used only for the startup and shutdown of the operations. Besides, it is composed of a combustion chamber for transformation of waste into ash and flue gas. The combustion chamber is equipped with an airflow passage, which provides oxygen for combustion. The thermal energy generated from the combustion of waste is transferred to steam in the boiler segment through superheater tubes, which is further used in electricity generation and heating. The hot flue gas is then passed through flue gas purification system (facilitated with water scrubber) for cleaning and lowering of temperature before being emitted to the atmosphere. The emitted gas consists of CO_2, N_2O, NO_x, NH_3, and organic C. Methane generation during waste incineration process is minimum and only arises in exceptional cases (from remain over waste in waste bunker), therefore quantitatively it is not regarded as climate relevant. In incineration unit, CO_2 constitutes the main climate-relevant emission. Moreover, the residues of the process include ash and flue gas purification residues. However, incineration is still not an ideal technology for municipal solid waste in many developing nations due to high proportion of food waste and moisture content. In Germany, incineration of 1 t of MSW was generally associated with the release of nearly 0.7–1.2 t of CO_2 [93]. Bogner et al. [5] estimated the release of GHG from waste incineration approximately 40 Mt CO_2e year^{-1}. The CO_2 emission from incineration unit in European Union was reported as 9 Mt CO_2e year^{-1} [20].

5.5 GHG Emissions from Landfill

Landfills are the significant contributors to anthropogenic climate change and one of the primary sources of global GHG emissions specially CH_4, accounting for 1–2% of total emissions [101]. The yet another large source of releases of CH_4 and N_2O from the waste sector is leachates from landfill sites [101]. The landfill GHG emissions are mainly influenced by landfill volume, age of the disposed waste, temperature, and moisture content [101]. In addition, fates of the carbon in the waste including carbon sequestered in landfills, in CO_2 from collection, decomposition, combustion and oxidation as well as in CH_4 emitted to the atmosphere, are the major determinants of GHG productions from landfills [101]. Therefore, different stages of MSW management also influence the emissions of GHGs from landfill sites [91]. Bogner et al. [5] reported that landfill CH_4 emission in Europe, the USA, and South Africa in the ranged between 0.1 and 1.0 t CH_4 ha^{-1} day^{-1}. Since 2009, British landfill greenhouse gas emissions have declined. Tiseo [86] found ~50% reduction in GHG emissions from 2009 (29 million metric tonne (MMt) CO_2e year^{-1}) to 2018 (14.1 MMt CO_2e year^{-1}) in the UK with the lowest emission recorded in year 2016 (13.9 MMt CO_2e year^{-1}). In a study conducted by [33] on landfills in different countries reported that CH_4 emission flux rates in South Africa, Japan, Florida, Taiwan, Thailand, Mexico, and Malaysia were 31.0, 0.21–266, 37.5, 0.38–89.5, 1030.6, and 0–1112 mg m^{-2} min^{-1}, respectively.

6 Case Studies

6.1 GHG Emissions from MSW Management in China

Liu et al. [58] analyzed the properties of MSW and GHG emissions during waste management in different areas of China through LCA approach using EaseTech software. The organic fraction and moisture contents in waste varied from 50 to 70% and >50%, respectively. It was revealed that GHG emissions during scenario 1 (landfilling with flaring) and 2 (landfilling with biogas recovery) were 192 and 117 kg CO_2e t^{-1} of waste, respectively. Scenario 4, i.e., incineration with 19% energy recovery rate led to a substantial decrease in gaseous emissions (−124 kg CO_2e t^{-1} of waste) and thus net GHG emission was 32 kg CO_2e CO_2e t^{-1} of waste. Due to the high consumption of energy and inevitable leakage of N_2O and CH_4 in the treatment process, the fifth scenario (anaerobic digestion of the biodegradable portions along with incineration of components having high calorific value followed by residue landfilling) resulted in GHG release of 67 kg CO_2e t^{-1} of waste.

Yu and Zhang [100] reported a gradual increase in the amount of MSW generation in Beijing from 1993 to 2013 having food waste as the most substantial component over the earlier decade. The study showed a substantial increase in GHG emission during the waste management from 1950 (6000 t CO_2e $year^{-1}$) to 2013 (2145000 t CO_2e $year^{-1}$) [100]. However, the scenario study showed reduction of 9.8, 22.7, and 4.5% GHG emissions through three techniques, i.e., energy recovery in incineration, gas flaring at landfills, and CH_4 recovery from landfill sites, respectively. The study recommended that utilization of wastes in ratio of 3:3:4 by composting, incineration and landfill can efficiently reduce the gaseous emission by 41% in the coming future [100].

6.2 GHG Emissions from MSW Management in the USA

Direct GHG emissions scenario of 2018 showed that CO_2 (2714003580 Mt CO_2e) is the highest emitted GHG followed by CH_4 (226971856 Mt CO_2e) and N_2O (28672148 Mt CO_2e) [91]. Waste sector stands at sixth position in terms of GHG emissions, i.e., on an average 108.9 MMt of GHG is emitted from 1498 facilities [91]. Table 4 shows GHG generations during the course of MSW management in the USA from 1990 to 2018 [90].

Table 4 Greenhouse gas emissions (MMt CO_2e) from municipal solid waste management sector in the USA from 1990 to 2018

GHGs emissions	1990	2005	2014	2015	2016	2017	2018
CO_2							
Fossil fuel combustion *(transportation, electric power generation, industrial, residential, commercial and US territories)*	4740.0	5740.0	5184.0	5031.8	4942.2	4892.2	5031.8
Petroleum systems	9.6	12.2	30.5	32.6	23.0	24.5	36.8
Natural gas systems	32.2	25.3	29.6	29.3	29.9	30.4	35.0
Incineration of waste	8.0	12.5	10.4	10.8	10.9	11.1	11.1
CH_4							
Landfills	179.6	131.3	112.6	111.3	108.0	107.7	110.6
Composting	0.4	1.9	2.1	2.1	2.3	2.4	2.5
Petroleum systems	46.1	38.8	43.5	40.5	39.0	38.7	36.2
Field burning of biomass	0.3	0.4	0.4	0.4	0.4	0.4	0.4
Natural gas systems	183.3	158.1	141.1	141.9	135.8	139.3	140.0
Petroleum systems	NA	NA	NA	NA	NA	NA	NA
N_2O							
Composting	0.3	1.7	1.9	1.9	2.0	2.2	2.2
Incineration of waste	0.5	0.4	0.3	0.3	0.3	0.3	0.3
Field burning of agricultural residues	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Petroleum systems	NA	NA	NA	NA	NA	NA	0.1
Natural gas systems	NA	NA	NA	NA	NA	NA	NA

Source US EPA [91]; NA: data not available

Lee et al. [56] used US-based annual figures during the period of 1990–2012 in order to substantiate the causal relationship between MSW management and GHG emissions. He implied that consistent increase in per capita generation of MSW in the USA from 1990 (208.3 kg) to 2012 (250.9 kg) was accompanied with concurrent increase in its recovery rate from 33.3 to 86.6% (increased by 160%). In addition, he marked a successive reduction in GHG emission from MSW management sector, i.e., 165 Tg CO_2e in 1990 to 124 Tg CO_2e in 2012. The study thus implies that decrease in waste generation with simultaneous increase in recycling rate could decrease the GHG releases from waste sector more efficiently.

A study conducted on waste-to-energy conversion technologies by [57] showed that landfill emissions of GHGs differ considerably by wastes' type. The study reported 65% reduction in GHGs from wood waste (i.e., from the amount of 2412 to 848 kg CO_2e t^{-1} dry mass), while 4% reduction in emission from food waste (i.e., from the amount of 2708 to 2603 kg CO_2e t^{-1} dry mass) [57]. However, LCA of waste-to-energy recovery reveals that cumulative application of gas collection from landfills and power generation can reduce GHG emissions from food waste by 44% (i.e., from 2708 to 1524 kg CO_2e t^{-1} dry mass) when compared with conventional landfilling of MSW [57].

6.3 GHG Emissions from MSW Management in India

Generation scenario of MSW in different states of India shows that Uttar Pradesh followed by Tamil Nadu, Maharashtra, Karnataka, and Delhi are the major contributors of generated MSW India. Ahluwalia and Patel [2] showed a trend of MSW generation in top five metropolitan cities as the highest in Delhi followed by Mumbai, Kolkata, Chennai, and Bengaluru in India (Table 5). In India, >60% of MSW constitutes organic material [8] (Fig. 7a). As per statistic 2014, MSW was majorly contributed by 51% biodegradable wastes, 10% plastics, 7% paper, and 32% other wastes such as textile, glass, metal, drain slit, street sweeping, and inert materials [70].

Annual report of 2016 from Municipal Corporation of different cities showed that door-to-door collection of wastes from households was facilitated in most of the cities in India and percentage of collected wastes varied from 25 to 100% depending upon the available resources [2] (Fig. 7b). While, more than 50% of waste segregation at source was expedited at Bengaluru and Mysuru of Karnataka, Pune of Maharashtra, Indore of Madhya Pradesh, Tirunelveli of Tamil Nadu, Alappuzha of Kerala, and Panaji of Goa. Installed capacity of compost plant in 20 states of India varied from 90 to 4,88,400 t $year^{-1}$ [17]. Furthermore, installed capacity of Biomethanation plants in Pune, Bengaluru, Solapur, and Chennai were 300, 250, 400, and 30 t day^{-1} [2]. Capacity of refused derived fuel in various cities in India was varied from 200 to 500 t day^{-1} [2]. Waste to energy recovery plants with capacity of 1300–2000, 1000–2400, 300, 600, and 70 t day^{-1} were installed with electricity generation unit of 14–24, 11–20, 2.9, 9, and 1.75 MW in Delhi, Hyderabad, Chennai, Jabalpur, and Shimla [2]. Total number of known landfill sites in different cities of India varies from 1 to 3 [14], and the amount of wastes discarded to landfills by different states is illustrated in Table 5. Emanations of GHGs during the management of MSW in varying regions of India are detailed in Table 6 [31]. Ahluwalia and Patel [2] reported that the emissions of GHGs from landfill sites in Delhi, Mumbai, Chennai, Bengaluru, Pune, Indore, and Chandigarh were 643.7, 920.8, 535.3, 337.3, 74.9, 56.2, and 36.1 kt CO_2e day^{-1}, respectively.

Table 5 Total municipal solid waste generation in different states of India from 2011 to 2015

States	Solid waste generation (tonne day^{-1})				Wastes disposed to landfill (%)			
	2011	2013	2014	2015	2011	2013	2014	2015
Andaman & Nicobar	117	126	130	134	100	96	96	96
Andhra Pradesh	16,152	17,724	8,335	8,739	77	47	23	94
Arunachal Pradesh	116	128	134	141	100	42	100	100
Assam	944	1,021	1,061	1,101	92	90	100	82
Bihar	3,912	4,291	4,486	4,684	100	100	100	100
Chandigarh	441	476	494	512	32	47	49	51
Chhattisgarh	1,912	2,122	2,230	2,340	87	92	92	65
Dadra & Nagar Haveli	55	81	95	108	100	100	100	100
Daman & Diu	82	129	153	177	100	100	100	100
Delhi	10,013	10,808	11,215	11,629	81	62	71	72
Goa	526	576	602	629	100	68	70	71
Gujarat	8,178	8,981	9,393	9,813	89	85	72	74
Haryana	3,986	4,447	4,684	4,926	100	87	96	96
Himachal Pradesh	200	211	217	222	23	29	42	44
Jammu & Kashmir	1,953	2,146	2,245	2,346	84	85	86	100
Jharkhand	2,980	3,250	3,389	3,530	98	98	98	98
Karnataka	9,889	10,769	11,220	11,679	79	81	73	69
Kerala	7,696	9,346	10,197	11,066	77	95	96	96
Lakshadweep	16	19	21	23	74	100	100	100
Madhya Pradesh	7,251	7,810	8,096	8,387	87	90	100	100
Maharashtra	18,407	19,747	20,434	21,131	89	76	71	67
Manipur	170	190	200	210	99	100	100	100
Meghalaya	217	236	246	256	54	59	78	86
Mizoram	153	166	173	180	100	100	100	100
Nagaland	104	121	130	138	100	85	100	100
Odisha	2,706	2,921	3,032	3,144	99	99	100	99
Puducherry	540	588	613	638	100	100	100	98
Punjab	5,469	5,892	6,108	6,329	100	99	94	100
Rajasthan	7,135	7,734	8,040	8,352	100	94	94	94
Sikkim	73	98	110	124	56	100	100	100
Tamil Nadu	18,612	20,097	20,858	21,632	97	92	92	93
Telangana	NA	NA	7,511	7,862	NA	NA	60	60

(continued)

Table 5 (continued)

States	Solid waste generation (tonne day^{-1})				Wastes disposed to landfill (%)			
	2011	2013	2014	2015	2011	2013	2014	2015
Tripura	413	487	526	565	90	100	52	56
Uttar Pradesh	20,135	21,816	22,677	23,553	100	76	77	92
Uttrakhand	1,014	1,122	1,178	1,234	100	100	100	100
West Bengal	15,924	17,282	17,978	18,686	96	92	95	95

Source GHG Platform, India [31]

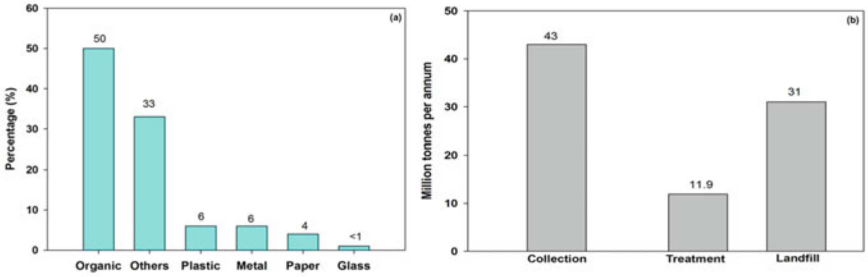

Fig. 7 Percentage contribution of organic and inorganic constituents in MSW generated from India and various treatment processes in the management of municipal solid waste (*Source* [8])

7 Ecological and Sociological Threats of GHG Emissions

The GHG emissions have far-ranging effects on the environment as well as socioeconomic facets due to their global warming as well as climate change potential, which subsequently affect ecological balance, change the biodiversity pattern, cause atmospheric pollution, and affect plant's and animals' health.

7.1 Global Warming

The GHG gases, in particular CO_2, are the most important anthropogenic gas whose atmospheric concentration has increased since preindustrial era [91]. Global atmospheric concentration of CO_2 has increased from a 354.39 to 414 ppm in past 10 years with simultaneous increase in concentrations of CH_4 and N_2O, which absorb outgoing radiant energy, thereby causing a decadal increase in atmospheric temperature by 0.33°C thus causing "Global Warming" [84]. The 100-year time horizon global warming potential (GWP) of CO_2, CH_4, and N_2O is 1, 28, and 265, respectively [42]. It is an amount of the energy absorbed by the emissions of 1 tonne of

Table 6 Total greenhouse gas emissions (t CO_2e per year) from municipal solid waste management in different states of India from 2011 to 2015

States	2011	2012	2013	2014	2015
Andaman & Nicobar	7,852	8,243	8,631	9,018	9,404
Andhra Pradesh	10,25,723	10,80,031	11,36,206	11,16,290	9,78,483
Arunachal Pradesh	7,000	7,410	7,834	7,611	8,164
Assam	62,809	66,051	69,314	72,604	75,926
Bihar	2,32,070	2,38,824	2,46,591	2,55,249	2,64,696
Chandigarh	26,154	24,447	23,101	23,312	23,795
Chhattisgarh	98,367	1,05,937	1,13,576	1,21,295	1,29,107
Dadra & Nagar Haveli	2,950	3,311	3,808	4,424	5,144
Daman & Diu	2,991	3,309	3,795	4,429	5,192
Delhi	6,10,636	6,38,815	6,67,456	6,80,558	7,12,649
Goa	34,435	36,396	38,402	40,270	42,367
Gujarat	4,17,262	4,33,590	4,51,332	4,70,339	4,90,485
Haryana	2,24,434	2,36,735	2,49,829	2,63,645	2,78,120
Himachal Pradesh	14,598	13,301	12,234	11,607	11,729
Jammu & Kashmir	1,24,559	1,31,506	1,38,663	1,46,021	1,53,572
Jharkhand	1,44,498	1,54,315	1,64,055	1,73,754	1,83,445
Karnataka	6,35,002	6,67,723	7,01,152	7,35,280	7,70,099
Kerala	4,62,821	5,01,480	5,45,873	5,95,354	6,49,379
Lakshadweep	930	1,001	1,083	1,174	1,273
Madhya Pradesh	4,63,048	4,81,145	4,99,869	5,19,180	5,39,043
Maharashtra	11,65,966	12,17,766	12,69,926	13,22,524	13,75,627
Manipur	10,918	11,576	12,267	12,989	13,740
Meghalaya	14,506	14,596	14,775	15,248	16,330
Mizoram	9,909	10,423	10,943	11,471	12,006
Nagaland	6,440	6,928	7,458	8,026	8,630
Odisha	1,52,486	1,58,378	1,64,523	1,70,901	1,77,493
Puducherry	34,819	36,621	38,460	40,337	42,251
Punjab	3,51,000	3,67,654	3,84,449	4,01,409	4,18,552
Rajasthan	3,76,944	3,90,384	4,04,732	4,19,895	4,35,799
Sikkim	3,751	3,938	4,227	4,870	5,584
Tamil Nadu	10,86,464	11,32,475	11,79,835	12,28,477	12,78,343
Telangana	–	–	–	–	85,330
Tripura	22,849	24,503	26,365	28,413	28,956

(continued)

Table 6 (continued)

States	2011	2012	2013	2014	2015
Uttar Pradesh	11,25,600	11,68,378	12,13,518	12,60,806	13,10,060
Uttrakhand	54,898	59,177	63,464	67,771	72,106
West Bengal	9,01,414	9,37,633	9,75,680	10,15,397	10,56,653
Total GHG emission	99,16,101	103,73,999	108,53,428	112,59,950	116,69,533

Source GHG Platform, India [31]

a gas over a given period of time with respect to the emissions of 1 tonne of CO_2. The higher is the GWP more is the absorbance of energy by the gas [91]. Increased concentrations of GHGs increase the temperature of the atmosphere leading to the warming of the earth's surface [84].

7.2 Carbon Cycle

Carbon dioxide, CH_4, and N_2O gases undergo natural cycle [84]. For instance, exchange of CO_2 between the atmosphere and the earth's surface involves several processes like respiration, photosynthesis, decomposition, and combustion. Relatively, constant amount of CO_2 is essential to carry out balanced carbon cycling in natural environment; however, its increased concentration due to anthropogenic input is sufficient enough to disrupt natural cycling [84].

7.3 Climate Change

Increase in the concentrations of GHGs and temperature is leading to global change in climatic pattern change (appropriately referred as "forcing climate change") to restore the balance between incoming and outgoing solar radiations. The forcing climate change is causing a change in cloud cover, wind speed, snowfall and rainfall pattern, sunshine hours and has also affected the normal weather pattern. Cumulatively, the change has knocked a drastic shift in climatic and weather pattern throughout the world [28, 66]. Forcing climate change has profound impacts on both terrestrial as well as aquatic ecosystems including world's oceans and their ecosystems.

7.4 Effects on the Aquatic Ecosystem

Studies have shown that since 1955, oceans have absorbed more than 80% of the heat [41]. Over the period of 1961–2003, the global average temperature of ocean up to the depth of 700 m has risen by 0.10 °C [41]. In aquatic environment, many organisms thrive within their range of temperature tolerance and any increase in their surrounding temperature may have negative impact on their physiological functioning, metabolic activities, reproductive pattern, and their survival [38, 99]. Yanik and Aslan [99] reported that increase in sea temperature and ocean acidification is the primary cause of global extinction of many marine life forms (e.g., phytoplankton, zooplankton, plants, and animals) and coral bleaching. In 2016, 16 and 54% of corals were totally and partially bleached, respectively, due to rise in temperature and CO_2 emission [7]

Warming of the ocean causes expansion of water and the addition of water due to melting of ice on land contributes in sea level rise [41]. GHG emissions and climate change have led to significant rise in sea surface level from 2010 (54.5 mm) to 2020 (95 mm) [85]. Rise in sea surface level results in erosion, flooding and drowning of low-lying coastal areas, higher storm-surge flooding, and landward intrusion of seawater into estuaries and aquifers, which in turn lead to habitat destruction and biodiversity loss [3, 7].

7.5 Effects on the Terrestrial Ecosystem

Global warming and change in climatic pattern accredited to increased GHGs emissions and release of other harmful constituents such NH_3 and volatile organic compounds (VOCs) have potential impact on terrestrial ecosystems' functioning. Emission of harmful constituents such as VOCs and NH_3 from different stages of MSW management causes contamination of air, water, and soil. The GHG emissions affect the evapotranspiration, net carbon storage, biodiversity pattern, species composition, nutrient cycling, and soil dynamics [43]. Wetland and terrestrial plants are the largest carbon sinks. However, both are also vulnerable to climatic variation accredited to global warming effects. Increase in GHG concentrations in atmosphere is variably and invariably affecting the various components of a plant's carbon budget including photosynthesis, respiration, biomass accumulation as well as allocation, metabolic functioning, decomposition, growth and reproductive development [43, 63].

7.6 Socioeconomic Impacts of GHGs

The GHG emissions from intermediate processes and landfills are sources for several socioeconomic impacts like human health issues due to the exposure to noxious gases and to the ground/surface water contamination by leachates [44]. Even though advanced waste management systems in developed countries are well designed to reduce emissions but emissions from waste collection points and landfill sites are of high concern regarding the health of the rag pickers and workers near these sites

[15]. The exposure to emissions either through direct contact or inhalation and/or ingestion of contaminated food and water cause several disease such as heart-related ailments, respiratory problems, skin irritation, metabolic dysfunction, congenital malformations, nonchromosomal birth defects, reduced birth weight, premature child, improper growth of child and cancers of the lung, stomach, liver, bile ducts, cervix, and prostate [15].

Greenhouse gas emissions from waste management system are captivated with large proportion of economic implications. In high-income countries, operating costs from collection to final disposal of waste range between US\$ 100 and 170 t^{-1}, while in low to middle income countries, it varies US\$ 20 and 50 t^{-1} [78]. Global warming and climatic change due to enhanced GHGs have significant effects on agriculture, fisheries, horticulture, forestry, animal, and human health, which put enormous burden on global economy.

8 Mitigation Strategies in GHG Emissions During MSW Management

Existing practices of waste management can deliver effective mitigation of GHG emissions from waste sector. A wide range of established, sustainable, and environmentally sound technologies are available to curb GHGs emissions in conjugation with facilitation of cobenefits such as environmental protection, public health, and sustainable development. Cumulatively, these available technologies have the potentiality to directly shrink GHG emissions (through improved landfill practices, gas recovery from landfills, and tautly engineered wastewater management system) or evade significant generation of GHGs (through state-of-the-art incineration, meticulous composting of organic waste, and expanded waste collection area coverage). Furthermore, minimization of waste, reutilization, and recycling represent significant steps with huge potential toward indirect minimization of GHG emissions. This is further attributed to the conservation of raw materials, avoidance of fossil fuel and improved energy as well as resource efficiency. In many developed countries, especially Japan and the EU, waste management policies are closely related to and integrated with climate policies such as IPCC, EPA, and World Bank (Table 7).

8.1 5-R Principle

The principles of the internationally recognized 5-R hierarchy emphasize upon the resource value and future management of MSW [1, 88]. It plays a vital role in the reduction of GHG gases and lessens the burden on waste management system (Table 7). The hierarchy was set to manage the MSW at different levels:

- Reduction of wastes at source

Table 7 Management strategies to combat greenhouse gas (GHGs) emissions from municipal solid waste management and subsequent benefit to environment and socioeconomic facets

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Expanded sanitation coverage	NA	• Minimize unmanaged disposal of waste in rural and urban areas • Offers job to many people • Minimize the detrimental effects on environment and human health • Maximize material and energy recovery from wastes and economic acquisition
5Rs (Refuse, Reduce, Reuse, Repurpose, and Recycle)	CO_2, CH_4, and N_2O	• Reduction in use of raw materials, energy, and economic acquisition • Offers job creation for more people with implementation of health and safety provisions • Reduce the burden on waste management system and landfill sites
Prohibition on uncontrolled disposal and open burning of waste	CO_2, CH_4, and N_2O	• Inculcation of alternate low cost technological innervations • Minimize the detrimental effects on environment and human health • Inhibit pathogen growth and disease vectors
Use of natural gas in place of petrol or diesel-based vehicles and hand cart system	CO_2, CH_4, and N_2O	• Minimizes environmental pollution • Diminishes emission of fluorinated gases • Regulation economic incentive • Creates job opportunities

(continued)

Table 7 (continued)

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Efficient waste segregation	CO_2, CH_4, and N_2O	• Regulation economic incentive • Reduce the burden on waste management system and landfill sites
Reduction in biodegradable waste which is landfilled	CO_2, CH_4, and N_2O	• Prevent microbial decomposition of organic matter and subsequent emission of CH_4 and N_2O • Regulation economic incentive • Reduces foul smell
Aerobic biological treatment of wastes	CO_2	• Although reduces CO_2 emissions but can emit N_2O and CH_4 under reduced aeration or anaerobic conditions • Reduces volume, stabilizes organic C, and destroys pathogens • Compost generation which can be used as fertilizer • Job creation • Foul odor reduction
Anaerobic biological treatment of wastes with energy recovery system	CH_4 and N_2O	• Even though minimizes CO_2 generation but if not properly managed, leads to enormous CH_4 emission • CH_4 in biogas can be used as fuels for • heat or electricity generation • Produce biosolid under controlled conditions • Job creation • Foul odor reduction • Job creation

(continued)

Table 7 (continued)

Policies and preventive measures	Minimization of GHGs	Environmental and Socio-economic benefit
Mandate in installation of incineration and thermal processing for waste-to-energy	CO_2, CH_4, and N_2O	• Reduce environmental pollution such as heavy metal contamination, atmospheric release of acid gases, dioxins and other noxious substituents • Potential odor reduction • Provide significant mitigation potential for the waste sector • Regulation economic incentive • Waste to energy recovery offers replacement of fossil fuels • Offers job creation for more people
Standards for combustion and landfill performance to harness gas with or without energy recovery	CH_4 (predominant), N_2O, and CO_2	• Regulation economic incentive • Waste to energy recovery reduce the burden of electricity generation and fuel combustion • Efficient and proper management of MSW with less adverse impact on environment and human health.

Sources Bogner et al. [5], Xin et al. [96], US EPA 92]

- Reutilization of wastes wherever possible
- Recycling of the end products toward their useful life
- Recovery of the energy or materials from the wastes
- Managing the residuals in an environmentally comprehensive way

8.2 Waste Segregation

Sorting of MSW into organic/biodegradable and nondegradable components at point source such as at domestic level are cooperative to their further segregation into biodegradable, combustible, recyclables, hazardous, infectious, and inert wastes. Segregation of wastes at waste facility center incurs energy, which in turn emits GHG gases to lesser extent but this step plays a substantial role in managing the waste at further levels and helps in minimizing CO_2, CH_4, and N_2O [5, 88]. The associated benefits of waste segregation in MSW management are stated in Table 7.

8.3 Improved Landfill Practices

In developing nations, mostly wastes are disposed of in an unscientific way after treatment, which lead to several environmental problems such as leaching, surface runoff, GHGs emissions, and ultimately affect the living beings. Developed nations such as the USA, Japan, European countries have scientifically engineered landfills for the disposal of wastes/residues. Sanitary landfill is protected with side and bottom liners where stabilized and unrecoverable waste is buried in layers following solid waste management guidelines [8]. The waste is compressed to save space and covered with an inert layer with vents for gases for recovery and a bottom drainage network to collect leachates.

From the waste sector, the major GHG emissions are landfill CH_4 and to lesser extent CO_2 and N_2O. There are primarily two key strategies to reduce CH_4 emission from landfill sites, i.e., reduction in the quantity of biodegradable waste and implementation of guidelines/standards/policies to reassure the retrieval of CH_4 from landfills. In the USA, Clean Air Act (CAA) and New Source Performance Standards (NSPS) are applied to landfill generation model to manage CH_4 emissions. Similarly, in European countries, there is a marked phase reduction in landfilled biodegradable wastes from 1995 to 2005 (by 50%) and 2016 (by 35%) following the European Union landfill directive (1999/31/EC) accompanied with collection and flaring of gases at landfill sites [5]. Recovery of gases and reduction in biodegradable components are beneficial to regulatory and economic incentives. Increased landfill taxes including landfilling cost in many countries of Europe have been implemented to combat the issue of high disposal at landfill sites [35]. Besides, an outreach program at regular time interval on landfill methane provides technical provision and resources to manage landfill gases. Being major source of GHG emissions, landfill CH_4 recovery along with reduction in biodegradable wastes and economic as well as regulatory incentives are the most probable options to combat the issues of global warming as well as climate change (Table 7).

8.4 Controlled Composting and Anaerobic Digestion

Aerobic composting produces CO_2 and to lesser extent CH_4 and N_2O. Poorly managed composting such as wet compost in warm countries results in even higher generation of N_2O and CH_4 [35, 64]. A study conducted at the Griffith University of Queensland, Australia showed high generation of CH_4 from unmanaged household compost bins [35]. Therefore, organic wastes at home must be routinely composted in aerated chamber. Composting in controlled manner is thus essential to reduce CO_2 emission and anaerobic is better substitute to aerobic composting. This not only reduced biodegradable proportion of waste but in absence of oxygen is essential, which offers twin benefits such as generation of CH_4, which can further be utilized as a source of energy and compost for organic farming. However, both anaerobic digestion and composting have their own advantages. Additional benefits of controlled composting are mentioned in Table 7.

8.5 Utilization of MSW Compost as Manure

Utilization of MSW compost as manure is receiving a greater attention due to less availability of land area for waste disposal, high waste management costs, and the associated environmental problems. Agricultural and horticultural utilization of MSW compost is one of the cost-operative and most promising options for MSW management [50, 83], which not only merely decreases the adverse effects of MSW on the society and environment but also supplements nutritive value to the land and plants. However, there are several studies that negate the agricultural application of MSW compost due to food chain contamination of heavy metals and faecal pathogens [79]. Gautam and Agrawal [26] exclaimed the utilization of MSW as compost for cultivation of oil yielding crops such as mustard, lemongrass, and vetiver to eliminate the food chain contamination of metals. The additional socioeconomic and environmental welfares of utilization of MSW compost at land application are illustrated in Table 7.

8.6 State-of-the-Art Incineration

Incineration is a thermal process under controlled condition of temperature and pressure to exploit the energy from postconsumer wastes. Incineration is a cost-incentive process with emission control; therefore its application in most of the developing nations has been restricted because of less availability of resources to install the incineration facilities in MSW management system. There must be subsidies for installation of incinerators in developed countries combined with environmental standards for energy efficiencies [91]. Tax exemptions must be applied for electricity generation using incinerators and for energy recovery from wastes [35]. In many European countries, landfill taxes have been implemented to alleviate the cost of landfilling and financial allocation has been made for the installation of incinerators, combustion chambers, and mechanical biological treatment infrastructure [35].

8.7 Reclamation of Abandoned Dumpsites by Vegetation

Landfilling is the most ordinarily used technique in some developed and most developing nations to manage MSW. The disposal of MSW in landfills entails a number of environmental issues such as noxious gaseous emissions including GHGs, leachates and surface runoff carrying contaminants contaminating water and soil. These problems raise concerns about harmful impacts on human health and plants. Landfill dumpsite can interrupt the vegetation pattern of native species and create space for invasive as well as synanthropic plant species. Even though engineered techniques are available to manage waste disposal sites but reclamation by vegetation is the only long-term and sustainable approach to manage such dumpsites [27]. Reclamation of dumpsites not only improves soil properties through mycorrhizal symbiosis and improved soil enzymatic activities but also prevents leaching and surface runoff. Besides, green cover, it reduces emission of GHGs from the disposal site [76, 77].

9 Conclusions

The municipal solid waste (MSW) is mainly categorized into inorganic and organic components and its physico–chemical properties are prominently influenced by the geographical location, economic development, climatic condition, cultural norms, and energy sources. Management of MSW includes collection, transportation, segregation, material recycling, anaerobic digestion, composting, incineration, and landfill with energy-recovery system, wherein disposal at landfill sites is the most common practice of waste management in most of the developing nations. The emanation of greenhouse gases (CH_4, CO_2, and N_2O) associated with MSW management is the fourth largest contributor of GHGs in atmosphere accountable for global warming as well as climate change and causes adverse effects on socioeconomic and environmental facets. Life cycle assessment of MSW management reveals that landfill ($CH_4 > CO_2 > N_2O$) followed by anaerobic digestion ($CH_4 > CO_2 > N_2O$), composting ($CO_2 > CH_4 > N_2O$), incineration (CO_2), and transportation (CH_4, CO_2, and N_2O) are major contributors to GHG emissions. Since GHG emissions are an escalating problem with simultaneous increase in MSW generation; it necessitates an urgent action to combat the issue globally. Inculcation of 5R principle, expansion of waste collection area, waste segregation at source, advanced inculcation in waste management system, utilization of compost as manure, and reclamation of abandoned landfills by vegetation are the sustainable options to mitigate the global issue of GHG emissions. Besides, awareness, implementation of strict norms, regulations, and policies would be additives in regulating the problem.

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