Carbon emissions reduction assessment via biogas production and resource recovery: the IPCC methodology

14

Denzel C. Makepa and Zviemurwi J. Chihambakwe
Department of Fuels and Energy Engineering, Chinhoyi University of Technology, Chinhoyi, Zimbabwe

14.1 Introduction

Climate change poses one of the most significant challenges of our time, driven primarily by the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere. Scientific consensus underscores the role of human activities, particularly the burning of fossil fuels and deforestation, in accelerating this phenomenon. The consequences of climate change are far-reaching and include rising global temperatures, shifting weather patterns, more frequent and severe extreme weather events, and biodiversity loss (Rakib et al., 2018). Urgent action is required to mitigate these impacts and safeguard the planet for future generations. Effective mitigation strategies aim to reduce GHG emissions, enhance resilience to climate impacts, transition to renewable energy sources, and promote sustainable practices across sectors. The need for comprehensive and concerted efforts to address climate change is undeniable, emphasizing the critical importance of implementing local, national, and global mitigation strategies.

Biogas production plays a vital role in addressing environmental challenges and promoting sustainable development by harnessing the potential of organic waste streams to generate renewable energy while mitigating GHG emissions. The biogas production process involves anaerobic digestion, wherein organic materials such as agricultural residues, food waste, and wastewater are broken down by microorganisms in the absence of oxygen, producing biogas—a mixture of methane and carbon dioxide (Kunatsa & Xia, 2022). By capturing methane emissions that would otherwise be released during anaerobic decomposition in landfills or wastewater treatment plants, biogas production helps to prevent the potent GHG from entering the atmosphere. This mitigation of methane emissions not only reduces the carbon footprint associated with waste management but also contributes to climate change mitigation efforts. Furthermore, the utilization of biogas as a renewable energy source displaces the need for fossil fuels in various applications, such as electricity generation, heating, and transportation, further reducing GHG emissions and promoting the transition toward a low-carbon economy (Kabeyi & Olanrewaju, 2022). Biogas

Innovations in the Global Biogas Industry. DOI: https://doi.org/10.1016/B978-0-443-22372-3.00015-7

production offers a sustainable solution for managing organic waste while simultaneously reducing GHG emissions and advancing renewable energy deployment.

A standardized carbon accounting methodology is paramount to addressing the challenge of accurately quantifying emissions reductions from biogas projects. Due to the complex nature of biogas production and resource recovery, varying methodologies and metrics have led to inconsistencies in emissions reporting, hindering the comparability and credibility of carbon reduction assessments. The introduction of the Intergovernmental Panel on Climate Change (IPCC) methodology for waste sector projects offers a comprehensive and internationally recognized framework for assessing GHG emissions (Levermore, 2008). Through the provision of standardized protocols, emission factors, and guidelines for data collection and analysis, the IPCC methodology enhances transparency, consistency, and accuracy in quantifying emissions reductions from biogas projects (Penteado et al., 2012). This facilitates informed decision-making, enables effective carbon management strategies, and contributes to advancing global efforts toward mitigating climate change.

This chapter serves as a pivotal resource, aiming to furnish readers with an in-depth comprehension of the methodologies and critical considerations necessary for accurately assessing carbon emissions reductions derived from biogas production and resource recovery endeavors. By delving into the intricacies of the IPCC methodology and its practical application in the evaluation of GHG impacts, the chapter endeavors to offer invaluable insights to stakeholders actively engaged in biogas projects. Through elucidating these methodologies, stakeholders are empowered to make informed decisions, enhancing their ability to navigate complex environmental challenges and steer their projects toward sustainable outcomes. Ultimately, the chapter plays a pivotal role in facilitating the transition toward a low-carbon future by equipping stakeholders with the knowledge and tools necessary to optimize biogas production processes and mitigate their environmental footprint effectively.

14.2 Intergovernmental panel on climate change methodology for assessing greenhouse gase impacts

The IPCC offers a comprehensive framework for evaluating GHG impacts, ensuring consistency and comparability across assessments. This section delves into the key components of the IPCC methodology, encompassing guidelines, calculation methods, system boundaries, scope of assessment, and metrics.

14.2.1 Guidelines and calculation methods

14.2.1.1 Emission factor approach

The emission factor approach is a foundational methodology championed by the IPCC for the assessment of GHG emissions tied to specific activities or processes.

This method relies on empirical data to establish emission factors, which represent the quantity of GHG emissions released per unit of activity or product. These factors serve as standardized metrics, enabling consistent comparison across different scenarios.

Emission factors are derived through various means, including direct field measurements, controlled laboratory experiments, and comprehensive literature reviews (Aliyu et al., 2019). Field measurements involve the direct quantification of emissions from sources such as industrial processes, transportation, or agricultural activities, utilizing instrumentation and sampling techniques. Laboratory experiments replicate specific conditions to elucidate emission mechanisms and quantify emission rates under controlled variables. Additionally, comprehensive literature reviews and data compilation efforts amalgamate existing scientific research, national inventories, and emissions databases to synthesize representative emission factors applicable across different regions and contexts.

In practical application, emission factors play a pivotal role in several key areas. They serve as fundamental inputs for compiling GHG inventories at various levels, from national to project-specific scales. These inventories provide crucial policy development, reporting, and mitigation planning data. Emission factors also inform scenario modeling exercises, enabling the projection of future emissions trajectories under different policy, technology, or socioeconomic scenarios (Tong et al., 2020). Integrating emission factors with activity data and other parameters, models can assess the potential impacts of various mitigation options.

Moreover, emission factors are indispensable in policy analysis and decision-making processes. Policymakers rely on these factors to quantify the emission intensity of different activities and sectors, helping prioritize mitigation measures effectively. Decision-makers utilize emission factor data to evaluate the effectiveness and cost-effectiveness of interventions aimed at reducing GHG emissions (Wynes et al., 2018).

When seeking reputable databases for emission factors, several sources are widely recognized and referenced in environmental research and policy-making. The IPCC Guidelines for National GHG Inventories provide comprehensive guidelines for estimating GHG emissions from various sources, including biodigesters (Eggleston et al., 2006). Additionally, the US Environmental Protection Agency Emission Factors for Biogas Systems offer specific emission factors for different types of biogas systems, which can be used to estimate GHG emissions from biodigesters (US, Environmental Protection Agency. GHG Emission Factors Hub, 2024). The European Environment Agency also provides emission factors and methodologies for estimating emissions from biogas production and utilization (Nielsen, 2013). These databases are essential tools for researchers and policymakers aiming to accurately assess and manage GHG emissions.

14.2.1.2 Tiered approach

Tiered Approach The IPCC methodology employs a tiered approach, providing a structured framework that offers flexibility tailored to varying levels of data availability, quality, and country-specific circumstances. This tiered approach encompasses three distinct tiers, each designed to accommodate different levels of data sophistication and analytical rigor (Fig. 14.1).

Tier 1 represents the foundational level of the tiered approach, utilizing default emission factors and activity data to estimate GHG emissions. This tier is particularly suitable for preliminary assessments or regions with limited data availability (Booysen et al., 2018). Default emission factors are standardized values derived from aggregated data and literature reviews, offering a convenient starting point for estimating emissions when site-specific information is lacking. Similarly, activity data at Tier 1 may be based on national or global averages, providing a broad overview of emissions without requiring extensive data collection efforts. For example, in the study by Torrellas et al. (2018), the Tier 1 approach used IPCC default data such as 100 kg N/head/year for nitrogen excreted per dairy cattle and 5.1 kg VS/head/day for volatile solid content in manure. These standardized values offer a convenient starting point but may not accurately reflect local conditions, leading to higher emission estimates compared to other tiers. While Tier 1 provides a rapid and accessible means of estimating emissions, its reliance on generic assumptions may result in less precise assessments compared to higher tiers (Obi-Njoku et al., 2024).

Tier 2 builds upon Tier 1 by incorporating country-specific data and employing improved methodologies to refine emission estimates. Analysts leverage localized emission factors and activity data at this tier to achieve greater accuracy and relevance. For instance, Torrellas et al. (2018) used regional data from Catalonia, where nitrogen excreted per dairy cattle was 80.22 kg N/head/year and the volatile solid content in manure was 4.45 kg VS/head/day. This regional specificity reduces the reliance on

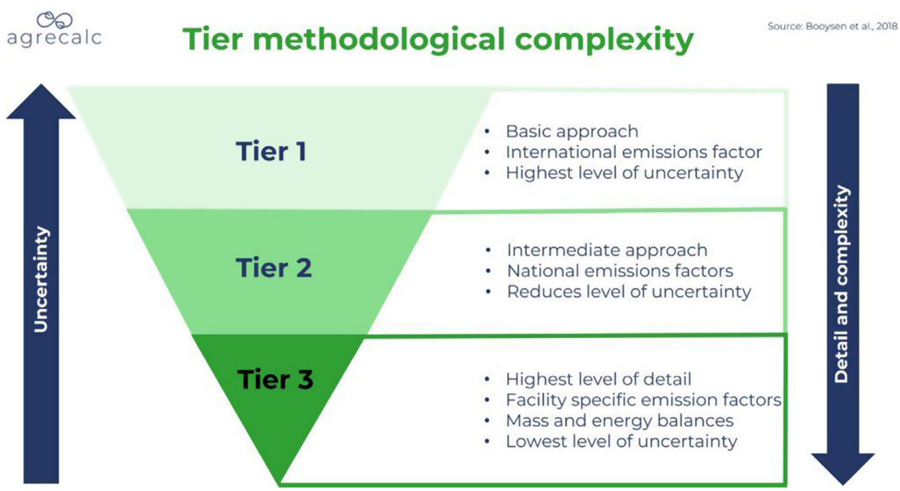

Figure 14.1 The tiered approach of the IPCC methodology.
Source: From Booysen, J., Booysen, W., & Kleingeld, M. (2018). A risk management strategy to identify and prioritise factors affecting industry's carbon tax liability. *South African Journal of Industrial Engineering, 29*(3), 26–39.

generic assumptions and improves the precision of the emission estimates. Country-specific data may include detailed information on industrial processes, energy consumption patterns, or agricultural practices, allowing for a more precise estimation of emissions within a given context (Obi-Njoku et al., 2024). Additionally, Tier 2 methodologies may involve more sophisticated modeling techniques or emission estimation protocols tailored to specific sectors or regions. Through the incorporation of country-specific data and methodologies, Tier 2 enhances the reliability and credibility of emission assessments, particularly in areas where default values may not accurately reflect local conditions (Obi-Njoku et al., 2024).

Tier 3 represents the highest level of the tiered approach, employing advanced models and detailed data to achieve the utmost accuracy and precision in emission estimation (Booysen et al., 2018). This tier is characterized by the utilization of state-of-the-art modeling tools, comprehensive datasets, and advanced analytical techniques. Analysts at Tier 3 may employ complex process-based models or sophisticated atmospheric dispersion models to simulate emissions from specific sources or activities. Detailed data inputs, such as site-specific measurements or remote sensing data, enable fine-scale resolution and spatially explicit emission estimates. In the study by Torrellas et al. (2018), the Tier 3 approach utilized analytical data, resulting in total excreted nitrogen of 148,109 kg N/y and total volatile solids of 2,318,869 kg VS/y. These detailed inputs enable fine-scale resolution and spatially explicit emission estimates, offering the highest accuracy. A study by Paredes et al. (2019) agrees with this finding that the IPCC Tier 1 method, using the recommended methane correction factor, highly overestimates CH_4 emissions compared with the values obtained on-site for estimating methane emissions from anaerobic sludge digesters. While Tier 3 requires significant expertise and resources, it provides unparalleled insight into emissions dynamics and facilitates targeted mitigation strategies at a granular level (Obi-Njoku et al., 2024).

The study by Torrellas et al. (2018) highlights the variability in emission estimates across different tiers. For instance, methane (CH_4) emissions calculated using the Tier 1 approach were 15% and 71% higher than those calculated using the Tier 2 and Tier 3 approaches, respectively. This significant difference illustrates how default values in Tier 1 can overestimate emissions compared to more refined data in higher tiers (Paredes et al., 2019). Similarly, ammonia (NH_3-N) and nitrous oxide (N_2O) emissions also varied across tiers. NH_3-N emissions were 4% higher in Tier 1 compared to Tier 3, and N_2O direct emissions were 46% higher in Tier 1 compared to Tier 3. This variability underscores the importance of using more specific and localized data in higher tiers to achieve accurate and reliable emission estimates.

14.2.1.3 Life cycle assessment

Life cycle assessment (LCA) is a critical tool acknowledged by IPCC guidelines for comprehensively evaluating the GHG impacts associated with products or processes throughout their entire lifecycle (Dong et al., 2019). This approach provides a holistic perspective by considering emissions from the production phase and all stages,

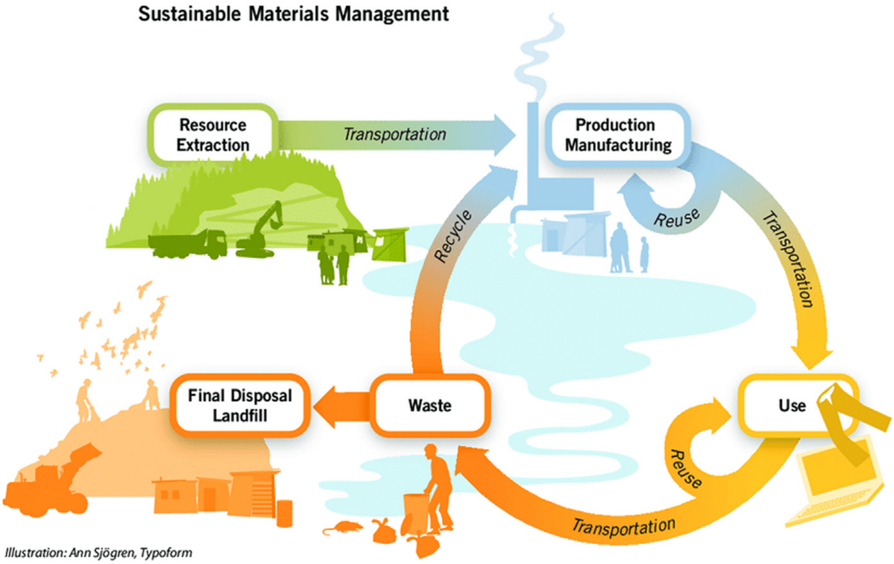

Figure 14.2 Life cycle assessment for holistic emission evaluation.
Source: From Slunge, D., & Wingqvist, G.Ö. (2011). *Governance bottlenecks and policy options for sustainable materials management. Centre for Environment and Sustainability (GMV)*. University of Gothenburg/Chalmers University of Technology.

including raw material extraction, production, transportation, product use, and end-of-life disposal (see Fig. 14.2) (Slunge & Wingqvist, 2011).

At its core, LCA seeks to quantify the environmental burdens associated with a product or process by examining inputs and outputs across its entire lifecycle (Dong et al., 2019). This encompasses the extraction and processing of raw materials, manufacturing processes, distribution, product use, and eventual disposal or recycling. Considering emissions and resource consumption at each stage of LCA provides insights into the overall environmental performance and identifies potential hotspots for emissions reduction or efficiency improvements (Obi-Njoku et al., 2024).

The first stage of an LCA involves defining the system boundaries and scope of the assessment and determining which processes and emissions sources will be included in the analysis (Makepa et al., 2023). This ensures that the assessment captures all relevant impacts and comprehensively understands the environmental footprint. Next, inventory data is collected for each stage of the lifecycle, including energy consumption, material inputs, emissions to air, water, and soil, and waste generation. This data is then processed to calculate the total environmental impacts, often using specialized software tools that apply emission factors and other conversion factors to the inventory data. Once the inventory analysis is complete, the environmental impacts are assessed using impact categories such as global warming potential (GWP), acidification potential, eutrophication potential, and others (Jang et al., 2022). These impact categories allow for a more nuanced understanding of the environmental consequences beyond just GHG emissions. Finally, the results of the LCA are interpreted and communicated to stakeholders, informing decision-making processes such as product design, supply chain management, and policy development (Diaz et al., 2021). Identifying opportunities for emissions reduction and resource efficiency improvements in LCA supports sustainable decision-making and the transition toward a low-carbon economy.

14.2.2 System boundaries and scope of assessment

In the assessment of GHG emissions, delineating system boundaries and defining the scope of assessment are essential steps in ensuring a comprehensive and accurate analysis. The IPCC methodology provides guidelines for establishing operational boundaries that encompass all relevant processes and emissions sources, thereby providing a clear framework for evaluating the environmental impact of biogas production and utilization.

Operational boundaries are defined to delineate the system under assessment, ensuring that all pertinent processes and emissions sources are included in the analysis. Within the context of biogas production and utilization, operational boundaries encompass both direct emissions from biogas production processes and indirect emissions from upstream and downstream activities (Feiz et al., 2020). Direct emissions typically include methane (CH_4) emissions from anaerobic decomposition of organic waste materials and carbon dioxide (CO_2) emissions from biogas combustion or flaring (Preble et al., 2020). Meanwhile, indirect emissions may arise from activities such as the production and transportation of feedstock materials, energy consumption in biogas production processes, and emissions associated with the distribution and utilization of biogas as an energy source (Roubík et al., 2020).

Moreover, the scope of assessment extends beyond direct emissions to encompass all GHGs relevant to climate change. This includes not only CO_2 and CH_4 but also other significant GHGs such as nitrous oxide (N_2O) and fluorinated gases (Tumendelger et al., 2019). In the context of biogas production and resource recovery, it is crucial to consider both biogenic and anthropogenic sources of GHGs. Biogenic sources refer to emissions derived from biological processes, such as methane emissions from anaerobic digestion. In contrast, anthropogenic sources stem from human activities, such as CO_2 emissions from fossil fuel combustion or N_2O emissions from agricultural practices (Hung & Subramanian, 2020).

IPCC guidelines emphasize the importance of considering both biogenic and anthropogenic sources of GHGs in order to provide a comprehensive assessment of the environmental impact of biogas production and resource recovery (Adams, 2018). Delineating clear operational boundaries and defining the scope of assessment to encompass all relevant processes and emissions sources help stakeholders to ensure that their analyses are comprehensive, transparent, and scientifically rigorous. This information is essential for informing policy decisions, guiding mitigation efforts, and promoting sustainable practices in the biogas sector.

14.2.3 Metrics for assessment

Metrics are pivotal in assessing GHG emissions and their impacts on climate change. The IPCC methodology promotes the use of specific metrics to standardize GHG emissions, enabling a thorough evaluation and comparison of mitigation strategies. Two key metrics highlighted by the IPCC are CO_2-equivalent (CO_{2e}) and GWP.

14.2.3.1 CO_2-equivalent (CO_2e)

The IPCC methodology employs CO_2e as a standardized metric for expressing GHG emissions in a unified unit. CO_2e is derived by converting emissions of different GHGs into their equivalent amounts of carbon dioxide (CO_2) based on their respective GWPs. This conversion accounts for variations in the potency of different GHGs in contributing to global warming over a specified time horizon. The IPCC methodology facilitates the aggregation of emissions from various GHGs, enabling a comprehensive assessment and comparison of mitigation options by expressing emissions in CO_2e (Lee et al., 2023). This standardized metric streamlines the analysis by providing a common basis for evaluating the climate impact of different emissions sources and mitigation strategies. It allows policymakers, researchers, and stakeholders to prioritize mitigation efforts effectively and identify the most cost-effective solutions for reducing GHG emissions.

14.2.3.2 Global warming potential (GWP)

The IPCC provides GWP values for different GHGs, representing their relative potency in contributing to global warming compared to CO_2 over a specified time horizon (e.g., 20, 100, or 500 years). GWPs are calculated based on the atmospheric lifetime and radiative forcing of each GHG, reflecting its ability to trap heat in the Earth's atmosphere. GWPs serve as multipliers used to convert emissions of non-CO_2 GHGs into CO_2-equivalents (Guest et al., 2013). Emissions of methane (CH_4), nitrous oxide (N_2O), fluorinated gases, and other GHGs can be quantified in terms of their equivalent impact on global warming relative to CO_2 by applying GWPs (Sovacool et al., 2021). This allows for a consistent and comparable assessment of emissions across different gases, considering their varying atmospheric lifetimes and radiative properties.

14.3 Biogas production process assessments

14.3.1 Methane capture and combustion emissions impacts

To understand its environmental implications, assessing the impacts of methane capture and combustion emissions is crucial in the biogas production process. Methane, a potent GHG produced during the anaerobic digestion of organic waste materials, is captured to mitigate emissions. Techniques such as gas sampling, emissions measurements, and flow monitoring are employed to quantify methane capture efficiency (Hammond et al., 2016). The effectiveness of methane capture systems depends on factors such as system design, operational efficiency, and maintenance practices. Methane capture offers significant emissions reduction potential by preventing the release of methane into the atmosphere. Biogas production facilities contribute to mitigating climate change impacts by capturing methane, a potent GHG. On the other hand, the combustion of biogas, primarily composed of methane and CO_2, is utilized as a renewable energy source for various applications such as electricity generation, heat production, or vehicle fuel (Kunatsa & Xia, 2022).

Assessment of combustion emissions involves quantifying the emissions generated during the combustion of biogas. Emission factors specific to biogas combustion are utilized to estimate CO_2 emissions per unit of energy produced. Additionally, other combustion byproducts, such as nitrogen oxides (NOx), particulate matter, and sulfur dioxide (SO_2), may also be assessed depending on combustion conditions and equipment (Paolini et al., 2018). The combustion of biogas offers environmental benefits compared to fossil fuel combustion, as it represents a renewable and low-carbon energy source. Biogas combustion reduces emissions of CO_2 and other pollutants associated with conventional energy production by displacing fossil fuels (Kabeyi & Olanrewaju, 2022). Through comprehensive assessments of methane capture efficiency and combustion emissions, stakeholders can quantify emissions reductions, identify opportunities for improvement, and make informed decisions to enhance the sustainability of biogas production projects.

14.3.2 Displacement of fossil fuel use for energy

A critical aspect of evaluating biogas production processes involves assessing how effectively biogas displaces fossil fuels for energy generation. This displacement is significant for various reasons, primarily due to the environmental and economic benefits it offers.

Biogas, derived from organic waste through anaerobic digestion, serves as a renewable energy source capable of substituting fossil fuels in diverse applications (Kunatsa & Xia, 2022). Biogas plays a crucial role in reducing GHG emissions and mitigating climate change by displacing fossil fuels. Compared to fossil fuel combustion, biogas combustion emits smaller amounts of carbon dioxide (CO_2) and other pollutants (Budzianowski & Postawa, 2017), thereby contributing to cleaner air and a healthier environment. Furthermore, the displacement of fossil fuels by biogas contributes to resource conservation and energy security. Utilizing biogas for energy generation reduces the demand for finite fossil fuel resources. Additionally, biogas production helps divert organic waste from landfills or incineration, reducing environmental pollution and conserving valuable landfill space.

Assessing the displacement of fossil fuels by biogas involves conducting energy balance analyses and emission reduction calculations. Energy balance analysis compares the energy content of biogas produced to the energy content of fossil fuels that would have been used for equivalent purposes, such as electricity generation or heating. Emission reduction calculations estimate the reduction in GHG emissions achieved by substituting fossil fuels with biogas, considering emission factors specific to fossil fuel combustion and biogas utilization.

The environmental benefits of fossil fuel displacement extend beyond GHG emissions reduction to include air quality, public health, and ecosystem integrity improvements. Moreover, assessing the economic viability of fossil fuel displacement involves comparing the costs of biogas production and utilization to those associated with fossil fuel extraction, processing, and consumption. Factors such as energy prices, government incentives, and technological advancements influence the economic feasibility of biogas projects and their competitiveness relative to fossil fuels (Rocha-Meneses et al., 2023).

14.3.3 Emissions from infrastructure and operations

Evaluating emissions from both infrastructure and operational activities is pivotal for comprehensively understanding the environmental implications of biogas production processes. This section delves into the emissions linked with the development of infrastructure, day-to-day operational endeavors, and the management practices crucial for biogas production.

During the construction phase of biogas facilities, emissions may arise from various activities, including site preparation, excavation, and the production of construction materials. Fuel combustion in machinery, material transportation, and energy consumption during construction contribute to these emissions. Additionally, the concept of embodied carbon encompasses emissions tied to the production and transportation of construction materials like concrete, steel, and piping. It involves quantifying emissions from these materials' extraction, processing, and transportation.

Once operational, biogas facilities require energy inputs for several processes, such as feedstock mixing, digester heating, and biogas compression (Bharathiraja et al., 2018). The assessment of energy consumption entails quantifying the usage of electricity, natural gas, or other energy sources essential for biogas facility operations. Furthermore, emissions, including methane and nitrous oxide, may be generated during the anaerobic digestion process, necessitating measures to minimize fugitive emissions and optimize digestion efficiency.

Effective management practices are critical for mitigating emissions from biogas production. This includes proper handling of digestate, the residual material from anaerobic digestion. Emissions associated with digestate storage, handling, and land application practices are evaluated to ensure compliance with environmental regulations and maximize resource recovery. Additionally, implementing emission reduction strategies, such as biogas utilization for heat and power generation and methane capture techniques, can significantly mitigate emissions from biogas production operations. Environmental impact assessments, particularly through LCA methodologies, play a vital role in quantifying the overall environmental impacts of biogas production processes. LCA considers emissions across the entire lifecycle of biogas production, from raw material extraction and facility construction to operation, maintenance, and end-of-life disposal (Dong et al., 2019). These assessments inform the development and implementation of mitigation strategies to minimize environmental impacts and enhance biogas project sustainability.

14.4 Resource recovery assessments

Resource recovery assessments play a pivotal role in evaluating the broader environmental benefits and sustainability implications of biogas production processes. This section focuses on three key aspects of resource recovery assessments: nutrient recycling and soil carbon impacts, substitution of synthetic fertilizers, and product lifecycle assessments of digestate uses, all of which are integral to assessing carbon emissions reductions from biogas production and resource recovery using the IPCC methodology.

14.4.1 Nutrient recycling and soil carbon impacts

Biogas production generates digestate, a nutrient-rich byproduct that contains valuable elements like nitrogen, phosphorus, and potassium. This digestate can be recycled and used as organic fertilizer in agricultural practices, thereby reducing reliance on synthetic fertilizers (Doyeni et al., 2021). The IPCC methodology recognizes the importance of nutrient recycling in mitigating carbon emissions by promoting sustainable agricultural practices. Assessing nutrient recycling involves quantifying the nutrient content of digestate and evaluating its effectiveness as a fertilizer. The need for synthetic fertilizers can be reduced, consequently lowering the carbon footprint associated with their production and application by recycling nutrients from biogas production back into the soil (Diacono et al., 2019). This contributes to carbon emissions reductions by minimizing the energy-intensive processes involved in synthetic fertilizer manufacturing.

Another crucial aspect of resource recovery assessments is evaluating the impacts of digestate application on soil carbon dynamics. When digestate is applied to agricultural soils, it can enhance soil organic matter content, leading to carbon sequestration (Slepetiene et al., 2022). This process involves capturing and storing carbon dioxide from the atmosphere in the soil, thereby mitigating GHG emissions. Assessing soil carbon impacts entails monitoring changes in soil organic carbon content, microbial activity, and soil fertility resulting from digestate application. The digestate contributes to sustainable agricultural practices while sequestering soil carbon, enhancing soil health and fertility (Egene et al., 2021). This aligns with the IPCC methodology's emphasis on assessing carbon emissions reductions from direct sources and indirect practices that enhance carbon sequestration.

14.4.2 Substitution of synthetic fertilizers

One of the key advantages of digestate is its potential to substitute synthetic fertilizers derived from fossil fuels. This substitution reduces the reliance on energy-intensive processes in synthetic fertilizer production, including extracting, processing, and transporting raw materials (Doyeni et al., 2021).

The IPCC methodology emphasizes the importance of assessing emissions reductions across all stages of the biogas production and utilization lifecycle. Substituting synthetic fertilizers with digestate directly contributes to emissions reductions by mitigating the carbon footprint associated with synthetic fertilizer production and application (Diacono et al., 2019). This aligns with the IPCC's goal of promoting sustainable practices that mitigate GHG emissions and combat climate change.

The substitution of synthetic fertilizers with digestate presents a range of environmental benefits. First, it reduces carbon emissions by diminishing the carbon footprint linked with synthetic fertilizer production and application. This reduction in carbon emissions aids in overall emissions reductions, aligning with efforts to mitigate climate change. Second, recycling nutrients from biogas production back into the soil conserves valuable resources and fosters sustainable agricultural practices. This nutrient recycling not only reduces the need for synthetic fertilizers but also helps maintain soil fertility over the long term, promoting ecosystem health and resilience. Third, digestate application enhances soil health by improving fertility, structure, and water retention capacity. This improvement in soil quality fosters a conducive environment for plant growth, increases crop yields, and enhances the soil's ability to withstand environmental stressors such as drought and erosion. Consequently, the overall resilience of agricultural systems is bolstered, contributing to long-term sustainability (Lamolinara et al., 2022).

14.4.3 Product lifecycle assessments of digestate uses

Digestate, produced during the anaerobic digestion process, contains valuable nutrients and organic matter that can be utilized in various applications, including agricultural fertilization, soil improvement, and energy production. Conducting product lifecycle assessments of digestate uses allows for a comprehensive evaluation of the environmental impacts associated with each application throughout its lifecycle.

Product lifecycle assessments of digestate uses involve quantifying and analyzing the environmental impacts associated with each stage of its lifecycle, from production and application to disposal or reuse. This includes assessing emissions associated with digestate storage, transportation, and application and evaluating its potential for emissions reduction and resource conservation compared to alternative practices (Cremiato et al., 2018). In the context of assessing carbon emissions reductions from biogas production and resource recovery using the IPCC methodology, product lifecycle assessments of digestate uses provide valuable insights into the carbon footprint of biogas projects. Quantifying the emissions associated with digestate utilization helps stakeholders determine the extent to which biogas production contributes to carbon emissions reductions compared to alternative waste management practices. Through product lifecycle assessments, stakeholders can optimize management practices to maximize resource recovery and minimize environmental impacts. Identifying the most sustainable and beneficial applications of digestate, such as agricultural fertilization or soil improvement, can also help stakeholders make informed decisions to enhance the environmental performance of biogas projects.

14.5 Sensitivity analysis of key parameters

Sensitivity analysis of key parameters is crucial in assessing carbon emissions reductions from biogas production and resource recovery using the IPCC methodology. This analysis evaluates the effect of various factors, including feedstock types, technology choices, and operational practices, on biogas projects' overall carbon emissions reduction potential. Additionally, understanding the uncertainty and limitations associated with these assessments is essential for ensuring the accuracy and reliability of the results.

14.5.1 Effect of feedstock

Different types of feedstocks used in biogas production can have varying carbon emissions reduction potentials (Budzianowski & Postawa, 2017). For example, organic wastes such as food scraps, agricultural residues, and livestock manure may yield different biogas production efficiencies and methane capture rates. Conducting sensitivity analyses allows stakeholders to assess how changes in feedstock composition and availability impact the overall carbon emissions reductions achieved by biogas projects. This information is vital for optimizing feedstock selection and management practices to maximize emissions reductions.

14.5.2 Effect of technology

The choice of biogas production technology also influences carbon emissions reductions. Different technologies, such as anaerobic digestion systems, vary in their efficiency, methane capture rates, and emissions control capabilities (Kumaran et al., 2016). Sensitivity analyses help evaluate how technological advancements or changes in system design affect the carbon emissions reduction potential of biogas projects. Comparing different technology options and their associated emissions profiles can help stakeholders make informed decisions to enhance the environmental performance of biogas production systems.

14.5.3 Effect of operations

Operational practices, including digester management, biogas utilization methods, and digestate management strategies, significantly impact carbon emissions reductions. Sensitivity analyses allow stakeholders to assess how changes in operational parameters, such as retention times, temperature control, and biogas utilization efficiency, affect emissions outcomes (Ardolino et al., 2021). Optimizing operational practices and implementing best management strategies can help stakeholders maximize carbon emissions reductions while ensuring efficient biogas production and resource recovery.

14.5.4 Uncertainty and limitations of assessments

It is crucial to acknowledge the uncertainties and limitations associated with carbon emissions reduction assessments for biogas projects. Factors such as variability in feedstock composition, technological performance, and operational conditions introduce uncertainties in emissions calculations (Adams & McManus, 2019).

A study conducted by Abdulla and Al-Ghazzawi (2000) identified several significant uncertainties regarding the applicability of the IPCC methodology in estimating methane emissions from domestic waste management facilities. The fraction of waste that undergoes anaerobic treatment depends heavily on the type of treatment technology employed. Different technologies have varying efficiencies and processes, leading to differences in how much waste is treated anaerobically. This variability introduces uncertainty in the estimation process as the proportion of waste treated anaerobically can significantly impact the amount of methane generated. The quantity and composition of waste deposited in landfills are not constant and can vary widely (Duan et al., 2021). Factors such as seasonal changes, regional differences, and changes in consumption patterns all contribute to this variability. Since the potential for methane production is closely linked to the organic content and overall composition of the waste, these fluctuations add another layer of uncertainty to the estimation of methane emissions. Estimating the actual quantity of methane produced from solid waste in landfills is inherently uncertain. This uncertainty arises from the complex biological processes involved in methane generation, which can be influenced by various factors including temperature, moisture content, and the presence of specific microbial communities (Feng et al., 2020). These factors can change over time and across different landfill sites, making it challenging to accurately predict methane production. Even if the quantity of methane produced can be estimated, the amount of methane that is eventually emitted into the atmosphere remains uncertain. This is because not all methane produced in a landfill necessarily escapes into the atmosphere. Some of it can be trapped within the landfill, some can be oxidized by microorganisms in the cover soil, and some can be captured and utilized through landfill gas recovery systems (Chetri & Reddy, 2021). The efficiency and extent of these processes can vary, leading to uncertainties in the actual emissions. The current IPCC methodology for estimating methane emissions from municipal solid waste (MSW) landfills does not adequately account for the potential oxidation of methane at the landfill site. Methane oxidation, carried out by methanotrophic bacteria in the landfill cover, can significantly reduce the amount of methane emitted to the atmosphere. Neglecting this factor can lead to an overestimation of methane emissions and consequently, an inaccurate assessment of the landfill's impact on GHG emissions.

Sensitivity analyses help identify these uncertainties and assess their potential impacts on emissions outcomes. Additionally, limitations in data availability, modeling assumptions, and measurement techniques may constrain the accuracy and reliability of emissions assessments. Stakeholders must transparently communicate these uncertainties and limitations to ensure the credibility and robustness of emissions reduction estimates.

Resource recovery assessments are essential for evaluating the environmental benefits and sustainability impacts of biogas production. The next section will explore a practical example: Case Study on the New Horizons Energy biogas plant in Cape Town, South Africa. This case study will provide insights into real-world applications and outcomes of biogas production and resource recovery.

14.6 Case study: new horizons energy biogas plant: Cape Town, South Africa

14.6.1 Case study description

In 2017, New Horizons Energy commissioned a groundbreaking biogas waste-to-energy (WtE) plant in Athlone Industria, located in the City of Cape Town. This innovative facility aimed to address environmental concerns while harnessing the potential of organic waste for energy production. The primary objective of the WtE plant was to process a significant portion of Cape Town's MSW using anaerobic digestion to produce biogas. Specifically, the plant targets the organic waste fraction, which constitutes approximately 10% of Cape Town's MSW, amounting to around 8000 tons/day. The WtE plant receives an average of 643 tons of waste daily, implementing advanced sorting and extraction processes to separate organic waste efficiently. Through these operations, the plant achieves an impressive 88% diversion rate from landfills, contributing significantly to waste management and environmental sustainability efforts in the region. One of the key outputs of the plant was biomethane, with a daily production capacity of approximately 670 m^3. This biomethane production translated to an annual energy output of 600 gigajoules (GJ), equivalent to a 5-megawatt biogas-to-electricity production capacity. The processed biomethane is not used for electricity generation but instead undergoes cleaning, upgrading, and pressurization to meet standards for use as a natural gas substitute. This final product, known as bio-compressed natural gas (Bio-CNG), is then sold to Afrox, contributing to the region's sustainable energy supply and reducing dependence on fossil fuels (Stafford, 2019).

14.6.2 Problem identification

The case study delves into a range of critical carbon emission challenges, with a particular focus on emissions stemming from waste management and energy production. Waste management presents a substantial environmental concern, as landfills and waste treatment processes release methane and other GHGs into the atmosphere. Through the examination of how biogas production and resource recovery can mitigate these emissions, the case study aims to pinpoint the opportunities and hurdles in transitioning toward more sustainable waste management practices. Furthermore, the study addresses carbon emissions associated with conventional energy production methods, highlighting the potential for biogas projects to offer cleaner and renewable energy alternatives that contribute to reducing overall carbon footprints in diverse sectors.

14.6.3 Methodology

To calculate the potential methane emissions from the 643 tons per day of organic waste that is diverted to the biogas plant instead of being sent to landfills, the IPCC methodology is utilized. This methodology provides a straightforward approach to estimating anthropogenic methane emissions from biomass through anaerobic decomposition. The equation used for estimating methane emissions from landfills according to the IPCC methodology is as follows (Johari et al., 2012):

$$CH_4\text{emissions, tonnes} = MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times 16/12 \quad (14.1)$$

where MSW_T represents the total amount of MSW generated in tons. MSW_F stands for the portion of this waste that is disposed of in landfills. MCF denotes the methane correction factor, while DOC indicates the proportion of degradable organic carbon in the waste. DOC_F represents the fraction of total degradable organic carbon that undergoes degradation, and F is the percentage of methane found in landfill gas.

The default values for MCF, ranging from 0.4 to 1.0, are contingent on the specific landfill practices associated with various types of MSW. When focusing on predominantly unmanaged landfills, an approximate value of 0.6 is recommended (Johari et al., 2012). As per the IPCC guidelines, the range for DOC lies between 0.08 and 0.21 and can be estimated through the following equation:

$$DOC = 0.4P + 0.15K + 0.3W \quad (14.2)$$

where P represents the proportion of papers in MSW, K stands for the fraction of kitchen garbage in MSW, and W denotes the fraction of wood/leaves in MSW. Additionally, it is important to account for DOC_F due to the gradual biodegradation of DOC over time. Therefore, a commonly used default value of 0.77 is recommended in such cases.

In this case study, to calculate the potential methane emissions from the 643 tons/day of organic waste diverted to the biogas plant instead of being sent to landfills, the IPCC methodology is utilized (Eq. 14.1). First, the daily waste is converted to an annual amount by multiplying the daily volume by the number of days in a year, resulting in 234,695 tons of MSW per year. According to the IPCC equation for estimating methane emissions, the values used are as follows: $MSW_T = 234{,}695$ tons/year, $MSW_F = 1$ (assuming all the waste is disposed of in landfills), $MCF = 0.6$ (for predominantly unmanaged landfills), $DOC = 0.21$ (assuming the higher end of the range for more organic waste), $DOC_F = 0.77$ (default value), and $F = 0.5$ (assuming 50% methane in landfill gas). Plugging these values into the equation yields 25,182 tons of CH_4 per year. Given that CH_4 has a GWP of 25 times that of CO_2 over a 100-year period, the methane emissions are converted to CO_2 equivalents using a factor of 25, resulting in 629,550 tons of CO_{2eq}/year. To determine the GWP per kilogram of MSW, the total CO_2 equivalent emissions are divided by the total annual MSW in kilograms, arriving at approximately 2.68 kg CO_{2eq}/kg MSW.

14.6.4 Discussion of carbon reduction potentials

According to the IPCC calculations, when waste is sent to a landfill, it leads to the generation of methane emissions totaling 25,182 tons annually. Converting this methane amount to its carbon dioxide equivalent (CO_{2eq}) using a GWP conversion factor of 25 (as per Solomon et al., 2007) results in an estimated 629,550 tons of CO_{2eq} emissions annually. This indicates that the waste contribution would have caused a GWP of approximately 2.68 kg CO_{2eq}/kg MSW.

Comparatively, previous studies have highlighted contrasting GWP values associated with biogas production and utilization. For example, Chaya & Gheewala (2007) reported a GWP of kg CO_{2eq}/kg MSW for biogas derived from MSW. Similarly, Wang et al. (2016) observed a GWP of 0.254 kg CO_{2eq}/kg feedstock for biogas produced from straw. Moreover, Lijó et al. (2014) found a negative GWP value of -0.0735 CO_{2eq}/kg feedstock for biogas derived from a combination of pig slurry and maize silage. These findings underscore the potential environmental benefits of biogas production and utilization compared to conventional waste management practices like landfilling, as evidenced by their lower or even negative GWP values.

14.6.4.1 Regional and global implications at scale

Biogas production and resource recovery initiatives, as demonstrated in this case study, have significant regional and global implications for carbon reduction. At a regional level, the adoption of biogas technologies and sustainable waste management practices can lead to substantial reductions in methane emissions, a potent GHG. Through the diversion of organic waste from landfills and utilizing it for biogas production, regions can not only mitigate methane emissions but also reduce the overall carbon footprint associated with waste management.

On a global scale, the widespread implementation of biogas projects and resource recovery systems has the potential to make a meaningful impact on climate change mitigation efforts. Biogas, as a renewable energy source, displaces fossil fuels, thereby reducing GHG emissions from energy production. Additionally, utilizing biogas-derived energy contributes to sustainable development goals by promoting energy access, reducing air pollution, and fostering economic growth in developed and developing regions.

14.6.4.2 Role in climate change mitigation strategies

Biogas production and resource recovery play a crucial role in broader climate change mitigation strategies. These initiatives align with the objectives outlined in international agreements such as the Paris Agreement, which emphasize the importance of reducing GHG emissions and transitioning to low-carbon energy systems. Through the capture of methane emissions from organic waste and converting them into biogas, carbon dioxide equivalent emissions can be significantly reduced. Furthermore, biogas projects contribute to the circular economy concept by closing the loop on waste streams and creating value from organic residues. This approach not only reduces GHG emissions but also promotes resource efficiency and environmental sustainability. Integrating biogas production into climate change mitigation strategies enhances resilience to climate impacts, improves energy security, and supports the transition to a low-carbon, sustainable future.

14.7 Conclusions

The assessment of carbon emissions reductions from biogas production and resource recovery using the IPCC methodology offers a comprehensive framework for evaluating the environmental impacts and sustainability implications of these initiatives. The IPCC methodology, with its guidelines, calculation methods, tiered approach, and metrics, provides a robust foundation for assessing GHG emissions, particularly focusing on carbon dioxide equivalent and GWP. Stakeholders can quantify emissions reductions, identify opportunities for improvement, and make informed decisions to enhance the sustainability of biogas production projects by employing emission factor approaches and conducting LCAs. Moreover, the displacement of fossil fuels, nutrient recycling, soil carbon impacts, and product lifecycle assessments of digestate uses are critical components in evaluating the broader environmental benefits and carbon emissions reductions achieved through biogas production and resource recovery. These assessments contribute to climate change mitigation strategies, promote sustainable waste management practices, and support the transition toward a low-carbon economy.

The case study of New Horizons Energy's biogas plant in Cape Town, South Africa, highlights the substantial potential for carbon emissions reductions through innovative WtE solutions. Through leveraging anaerobic digestion to convert organic waste into biogas and Bio-CNG, the plant has achieved remarkable success in diverting waste from landfills and producing renewable energy. At a regional and global scale, biogas production and resource recovery initiatives offer substantial carbon reduction potentials and contribute to climate change mitigation strategies. These initiatives align with international agreements and sustainable development goals by reducing GHG emissions, promoting energy access, and fostering economic growth. While acknowledging uncertainties and limitations in emissions assessments, the case study underscores the pivotal role of biogas projects in transitioning toward low-carbon, sustainable waste management and energy systems (Adams & McManus, 2019; Ardolino et al., 2021; Budzianowski & Postawa, 2017; Kumaran et al., 2016).

References

Abdulla, F. A., & Al-Ghazzawi, Z. D. (2000). Methane emissions from domestic waste management facilities in Jordan—Applicability of IPCC methodology. *Journal of the Air and Waste Management Association*, *50*(2), 234–239. Available from https://doi.org/10.1080/10473289.2000.10464011.

Adams, P. (2018). *GHG emissions from biomethane gas-to-grid injection via anaerobic digestion greenhouse gas. Balances of bioenergy systems* (pp. 141−158). Elsevier Inc.. Available from http://www.sciencedirect.com/science/book/9780081010365, https://doi.org/10.1016/B978-0-08-101036-5.00009-4.

Adams, P. W. R., & McManus, M. C. (2019). Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize. *Journal of Cleaner Production*, *218*, 529−542. Available from https://doi.org/10.1016/j.jclepro.2018.12.232, https://www.journals.elsevier.com/journal-of-cleaner-production.

Aliyu, G., Luo, J., Di, H. J., Lindsey, S., Liu, D., Yuan, J., Chen, Z., Lin, Y., He, T., Zaman, M., & Ding, W. (2019). Nitrous oxide emissions from China's croplands based on regional and crop-specific emission factors deviate from IPCC 2006 estimates. *Science of the Total Environment*, *669*, 547−558. Available from https://doi.org/10.1016/j.scitotenv.2019.03.142, http://www.elsevier.com/locate/scitotenv.

Ardolino, F., Cardamone, G. F., Parrillo, F., & Arena, U. (2021). Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective. *Renewable and Sustainable Energy Reviews*, *139*, 110588. Available from https://doi.org/10.1016/j.rser.2020.110588.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S., & Iyyappan, J. (2018). Biogas production—A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and Sustainable Energy Reviews*, *90*, 570−582. Available from https://doi.org/10.1016/j.rser.2018.03.093, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Booysen, J., Booysen, W., & Kleingeld, M. (2018). A risk management strategy to identify and prioritise factors affecting industry's carbon tax liability. *South African Journal of Industrial Engineering*, *29*(3), 26−39. Available from https://doi.org/10.7166/29-3-2046, https://journals.co.za/deliver/fulltext/indeng_v29_n3_a4.pdf?itemId = /content/journal/10520/EJC-1211fa57a6&mimeType = pdf&containerItemId = content/journal/indeng.

Budzianowski, W. M., & Postawa, K. (2017). Renewable energy from biogas with reduced carbon dioxide footprint: Implications of applying different plant configurations and operating pressures. *Renewable and Sustainable Energy Reviews*, *68*, 852−868. Available from https://doi.org/10.1016/j.rser.2016.05.076, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Chaya, W., & Gheewala, S. H. (2007). Life cycle assessment of MSW-to-energy schemes in Thailand. *Journal of Cleaner Production*, *15*(15), 1463−1468. Available from https://doi.org/10.1016/j.jclepro.2006.03.008.

Chetri, J. K., & Reddy, K. R. (2021). Advancements in municipal solid waste landfill cover system: A review. *Journal of the Indian Institute of Science*, *101*(4), 557−588. Available from https://doi.org/10.1007/s41745-021-00229-1, http://www.springer.com/41745.

Cremiato, R., Mastellone, M. L., Tagliaferri, C., Zaccariello, L., & Lettieri, P. (2018). Environmental impact of municipal solid waste management using life cycle assessment: The effect of anaerobic digestion, materials recovery and secondary fuels production. *Renewable Energy*, *124*, 180−188. Available from https://doi.org/10.1016/j.renene.2017.06.033, http://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews/.

Diacono, M., Persiani, A., Testani, E., Montemurro, F., & Ciaccia, C. (2019). Recycling agricultural wastes and by-products in organic farming: Biofertilizer production, yield performance and carbon footprint analysis. *Sustainability*, *11*(14), 3824. Available from https://doi.org/10.3390/su11143824.

Diaz, A., Schöggl, J. P., Reyes, T., & Baumgartner, R. J. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. *Sustainable Production and Consumption*, *26*, 1031–1045. Available from https://doi.org/10.1016/j.spc.2020.12.044, http://www.journals.elsevier.com/sustainable-production-and-consumption/.

Dong, Y., Hauschild, M., Sørup, H., Rousselet, R., & Fantke, P. (2019). Evaluating the monetary values of greenhouse gases emissions in life cycle impact assessment. *Journal of Cleaner Production*, *209*, 538–549. Available from https://doi.org/10.1016/j.jclepro.2018.10.205.

Doyeni, M. O., Stulpinaite, U., Baksinskaite, A., Suproniene, S., & Tilvikiene, V. (2021). The effectiveness of digestate use for fertilization in an agricultural cropping system. *Plants*, *10*(8), 1734. Available from https://doi.org/10.3390/plants10081734.

Duan, Z., Scheutz, C., & Kjeldsen, P. (2021). Trace gas emissions from municipal solid waste landfills: A review. *Waste Management*, *119*, 39–62. Available from https://doi.org/10.1016/j.wasman.2020.09.015.

Egene, C. E., Sigurnjak, I., Regelink, I. C., Schoumans, O. F., Adani, F., Michels, E., Sleutel, S., Tack, F. M. G., & Meers, E. (2021). Solid fraction of separated digestate as soil improver: implications for soil fertility and carbon sequestration. *Journal of Soils and Sediments*, *21*(2), 678–688. Available from https://doi.org/10.1007/s11368-020-02792-z, http://www.springerlink.com/content/1439-0108.

Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *IPCC guidelines for national greenhouse gas inventories*. IGES.

Feiz, R., Johansson, M., Lindkvist, E., Moestedt, J., Påledal, S. N., & Svensson, N. (2020). Key performance indicators for biogas production—Methodological insights on the life-cycle analysis of biogas production from source-separated food waste. *Energy*, *200*. Available from https://doi.org/10.1016/j.energy.2020.117462, https://www.journals.elsevier.com/energy.

Feng, H., Guo, J., Han, M., Wang, W., Peng, C., Jin, J., Song, X., & Yu, S. (2020). A review of the mechanisms and controlling factors of methane dynamics in forest ecosystems. *Forest Ecology and Management*, *455*, 117702. Available from https://doi.org/10.1016/j.foreco.2019.117702.

Guest, G., Cherubini, F., & Strømman, A. H. (2013). Global warming potential of carbon dioxide emissions from biomass stored in the anthroposphere and used for bioenergy at end of life. *Journal of Industrial Ecology*, *17*(1), 20–30. Available from https://doi.org/10.1111/j.1530-9290.2012.00507.x, http://www.interscience.wiley.com/jpages/1088-1980.

Hammond, K. J., Crompton, L. A., Bannink, A., Dijkstra, J., Yáñez-Ruiz, D. R., O'Kiely, P., Kebreab, E., Eugène, M. A., Yu, Z., Shingfield, K. J., Schwarm, A., Hristov, A. N., & Reynolds, C. K. (2016). Review of current in vivo measurement techniques for quantifying enteric methane emission from ruminants. *Animal Feed Science and Technology*, *219*, 13–30. Available from https://doi.org/10.1016/j.anifeedsci.2016.05.018.

Hung, Y.-T., & Subramanian, A. (2020). *Agricultural sources of greenhouse gases* (pp. 483–529). World Scientific Pub Co Pte Lt. Available from http://doi.org/10.1142/9789811207136_0013.

Jang, H. J., Ahn, Y. H., & Tae, S. H. (2022). Proposal of major environmental impact categories of construction materials based on life cycle impact assessments. *Materials*, *15*(14). Available from https://doi.org/10.3390/ma15145047, http://www.mdpi.com/journal/materials.

Johari, A., Ahmed, S. I., Hashim, H., Alkali, H., & Ramli, M. (2012). Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. *Renewable and Sustainable Energy Reviews*, *16*(5), 2907–2912. Available from https://doi.org/10.1016/j.rser.2012.02.005.

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Biogas production and applications in the sustainable energy transition. *Journal of Energy*, *2022*, 1–43. Available from https://doi.org/10.1155/2022/8750221.

Kumaran, P., Hephzibah, D., Sivasankari, R., Saifuddin, N., & Shamsuddin, A. H. (2016). A review on industrial scale anaerobic digestion systems deployment in Malaysia: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, *56*, 929–940. Available from https://doi.org/10.1016/j.rser.2015.11.069, https://www.journals.elsevier.com/renewable-and-sustainable-energy-reviews.

Kunatsa, T., & Xia, X. (2022). A review on anaerobic digestion with focus on the role of biomass co-digestion, modelling and optimisation on biogas production and enhancement. *Bioresource Technology*, *344*, 126311. Available from https://doi.org/10.1016/j.biortech.2021.126311.

Lamolinara, B., Pérez-Martínez, A., Guardado-Yordi, E., Guillén Fiallos, C., Diéguez-Santana, K., & Ruiz-Mercado, G. J. (2022). Anaerobic digestate management, environmental impacts, and techno-economic challenges. *Waste Management*, *140*, 14–30. Available from https://doi.org/10.1016/j.wasman.2021.12.035, http://www.elsevier.com/locate/wasman.

Lee, H., Calvin, K., Dasgupta, D., Krinmer, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., & Barret, K. (2023). *Synthesis report of the IPCC Sixth Assessment Report (AR6), Longer report*. IPCC.

Levermore, G. J. (2008). A review of the IPCC Assessment Report Four, Part 1: the IPCC process and greenhouse gas emission trends from buildings worldwide. *Building Services Engineering Research and Technology*, *29*(4), 349–361. Available from https://doi.org/10.1177/0143624408096263.

Lijó, L., González-García, S., Bacenetti, J., Fiala, M., Feijoo, G., & Moreira, M. T. (2014). Assuring the sustainable production of biogas from anaerobic mono-digestion. *Journal of Cleaner Production*, *72*, 23–34. Available from https://doi.org/10.1016/j.jclepro.2014.03.022, https://www.journals.elsevier.com/journal-of-cleaner-production.

Makepa, D. C., Chihobo, C. H., Manhongo, T. T., & Musademba, D. (2023). Life-cycle assessment of microwave-assisted pyrolysis of pine sawdust as an emerging technology for biodiesel production. *Results in Engineering*, *20*. Available from https://doi.org/10.1016/j.rineng.2023.101480, https://www.journals.elsevier.com/results-in-engineering.

Nielsen, O.-K. (2013). *EMEP/EEA air pollutant emission inventory guidebook 2013. Technical guidance to prepare national emission inventories*. EMEP/EEA.

Obi-Njoku, O., Boh, M. Y., Smith, W., Grant, B., Flemming, C., Price, G. W., Hernandez-Ramirez, G., Burton, D., Whalen, J. K., & Clark, O. G. (2024). A comparison of Tier 1, 2, and 3 methods for quantifying nitrous oxide emissions from soils amended with biosolids. *Science of the Total Environment*, *915*. Available from https://doi.org/10.1016/j.scitotenv.2023.169639, https://www.sciencedirect.com/science/journal/00489697.

Paolini, V., Petracchini, F., Segreto, M., Tomassetti, L., Naja, N., & Cecinato, A. (2018). Environmental impact of biogas: A short review of current knowledge. *Journal of Environmental Science and Health, Part A*, *53*(10), 899–906. Available from https://doi.org/10.1080/10934529.2018.1459076.

Paredes, M. G., Güereca, L. P., Molina, L. T., & Noyola, A. (2019). Methane emissions from anaerobic sludge digesters in Mexico: On-site determination vs. IPCC Tier 1 method. *Science of The Total Environment*, *656*, 468–474. Available from https://doi.org/10.1016/j.scitotenv.2018.11.373.

Penteado, R., Cavalli, M., Magnano, E., & Chiampo, F. (2012). Application of the IPCC model to a Brazilian landfill: First results. *Energy Policy*, *42*, 551–556. Available from https://doi.org/10.1016/j.enpol.2011.12.023.

Preble, C. V., Chen, S. S., Hotchi, T., Sohn, M. D., Maddalena, R. L., Russell, M. L., Brown, N. J., Scown, C. D., & Kirchstetter, T. W. (2020). Air pollutant emission rates for dry anaerobic digestion and composting of organic municipal solid waste. *Environmental Science and Technology*, *54*(24), 16097−16107. Available from https://doi.org/10.1021/acs.est.0c03953, http://pubs.acs.org/journal/esthag.

Rakib, M. R., Islam, M. N., Parvin, H., & van Amstel, A. (2018). *Climate change impacts from the global scale to the regional scale: Bangladesh*. *Springer climate* (pp. 1−25). Bangladesh: Springer. Available from https://rd.springer.com/bookseries/11741, https://doi.org/10.1007/978-3-319-26357-1_1.

Rocha-Meneses, L., Luna-delRisco, M., González, C. A., Moncada, S. V., Moreno, A., Sierra-Del Rio, J., & Castillo-Meza, L. E. (2023). An overview of the socio-economic, technological, and environmental opportunities and challenges for renewable energy generation from residual biomass: A case study of biogas production in Colombia. *Energies*, *16*(16). Available from https://doi.org/10.3390/en16165901, http://www.mdpi.com/journal/energies/.

Roubík, H., Barrera, S., Van Dung, D., Phung, L. D., & Mazancová, J. (2020). Emission reduction potential of household biogas plants in developing countries: The case of central Vietnam. *Journal of Cleaner Production*, *270*, 122257. Available from https://doi.org/10.1016/j.jclepro.2020.122257.

Slepetiene, A., Kochiieru, M., Jurgutis, L., Mankeviciene, A., Skersiene, A., & Belova, O. (2022). The effect of anaerobic digestate on the soil organic carbon and humified carbon fractions in different land-use systems in Lithuania. *Land*, *11*(1), 133. Available from https://doi.org/10.3390/land11010133.

Solomon, S.D., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., & Miller, H.L. (2007). IPCC, 2007: *Climate change 2007. The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Slunge, D., & Wingqvist, G. Ö. (2011). *Governance bottlenecks and policy options for sustainable materials management. Centre for Environment and Sustainability (GMV)*. University of Gothenburg/Chalmers University of Technology.

Sovacool, B. K., Griffiths, S., Kim, J., & Bazilian, M. (2021). Climate change and industrial F-gases: A critical and systematic review of developments, sociotechnical systems and policy options for reducing synthetic greenhouse gas emissions. *Renewable and Sustainable Energy Reviews*, *141*, 110759. Available from https://doi.org/10.1016/j.rser.2021.110759.

Stafford, W. H. L. (2019). *WtE best practices and perspectives in Africa*. *Municipal solid waste energy conversion in developing countries: Technologies, best practices, challenges and policy* (pp. 185−217). South Africa: Elsevier. Available from https://www.routledge.com/products/, https://doi.org/10.1016/B978-0-12-813419-1.00006-1.

Tong, D., Cheng, J., Liu, Y., Yu, S., Yan, L., Hong, C., Qin, Y., Zhao, H., Zheng, Y., Geng, G., Li, M., Liu, F., Zhang, Y., Zheng, B., Clarke, L., & Zhang, Q. (2020). Dynamic projection of anthropogenic emissions in China: methodology and 2015−2050 emission pathways under a range of socio-economic, climate policy, and pollution control scenarios. *Atmospheric Chemistry and Physics*, *20*(9), 5729−5757. Available from https://doi.org/10.5194/acp-20-5729-2020.

Torrellas, M., Burgos, L., Tey, L., Noguerol, J., Riau, V., Palatsi, J., Antón, A., Flotats, X., & Bonmatí, A. (2018). Different approaches to assess the environmental performance of a cow manure biogas plant. *Atmospheric Environment*, *177*, 203−213. Available from https://doi.org/10.1016/j.atmosenv.2018.01.023.

Tumendelger, A., Alshboul, Z., Lorke, A., & Kuramae, E. E. (2019). Methane and nitrous oxide emission from different treatment units of municipal wastewater treatment plants in Southwest Germany. *PLoS ONE*, *14*(1), e0209763. Available from https://doi.org/10.1371/journal.pone.0209763.

US, Environmental Protection Agency. (2024). *GHG emission factors hub*. EPA.

Wang, Q. L., Li, W., Gao, X., & Li, S. J. (2016). Life cycle assessment on biogas production from straw and its sensitivity analysis. *Bioresource Technology*, *201*, 208−214. Available from https://doi.org/10.1016/j.biortech.2015.11.025, http://www.elsevier.com/locate/biortech.

Wynes, S., Nicholas, K. A., Zhao, J., & Donner, S. D. (2018). Measuring what works: Quantifying greenhouse gas emission reductions of behavioural interventions to reduce driving, meat consumption, and household energy use. *Environmental Research Letters*, *13*(11). Available from https://doi.org/10.1088/1748-9326/aae5d7, http://iopscience.iop.org/article/10.1088/1748-9326/aae5d7/pdf.