Anaerobic Digestion: Climate Change Mitigation Through Sustainable Organic Waste Valorization

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Abstract

A tremendous amount of organic waste produced annually is often burned in the open or disposed in unmanaged open dumps, landfills, and wastewater streams. Organic waste naturally decomposes to release greenhouse gases that contribute to climate change. However, organic waste can be anaerobically digested to produce methane, which can be captured and utilized as an alternative to fossil fuel-derived energy. Moreover, an additional product of anaerobic digestion, digestate, can be utilized as a soil ameliorant. This chapter provides an overview of the multi-faceted benefits of using anaerobic digestion as a nature-based solution to climate change mitigation through the valorization of organic wastes that emit greenhouse gases. Insights into some opportunities and challenges that are associated with anaerobic digestion as a solution for lowering greenhouse gas emissions are also discussed.

Keywords

Organic waste · Anaerobic digestion · Waste valorization · Climate change · Renewable energy · Greenhouse gases · Emissions · Methane · Digestate

Introduction

Climate change is driven by the emission of greenhouse gases (GHGs) such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases contribute to increasing global temperatures and subsequent water shortages, loss of biodiversity, disruption of food systems, health risks, poverty, and extreme weather events such as cyclones, droughts, and floods (Masson-Delmotte et al. 2021). Globally, the equivalent of approximately 50 billion metric tons of CO_2 in total was emitted in 2016 (Ritchie and Roser 2020). Sectors contributing to this total include energy (use in industry, transportation, buildings, and other energy production sources); agriculture, forestry, and other land use; industrial processes and waste (Fig. 1). The energy sector produced the largest amount of GHGs (73.2%), while it was reported that the food production sector alone constituting supply chain; livestock and fisheries; crop production; and land use accounted for 26% of the global GHG emissions of which 6% is derived from food losses and waste (Poore and Nemecek 2018).

Organic wastes such as animal manure, food waste, and municipal wastewater naturally decompose because of microbial activity resulting in the emission of GHGs. Many nature-based solutions are being explored to mitigate climate change. One such solution is anaerobic digestion, which provides a circular approach to waste management and energy and nutrient recovery. The anaerobic digestion process involves microbial degradation and transformation of organic waste under low oxygen conditions into CH_4, CO_2, and trace amounts of other gases (Roopnarain et al. 2021). In the first stage of anaerobic digestion, proteins, fats, and carbohydrates

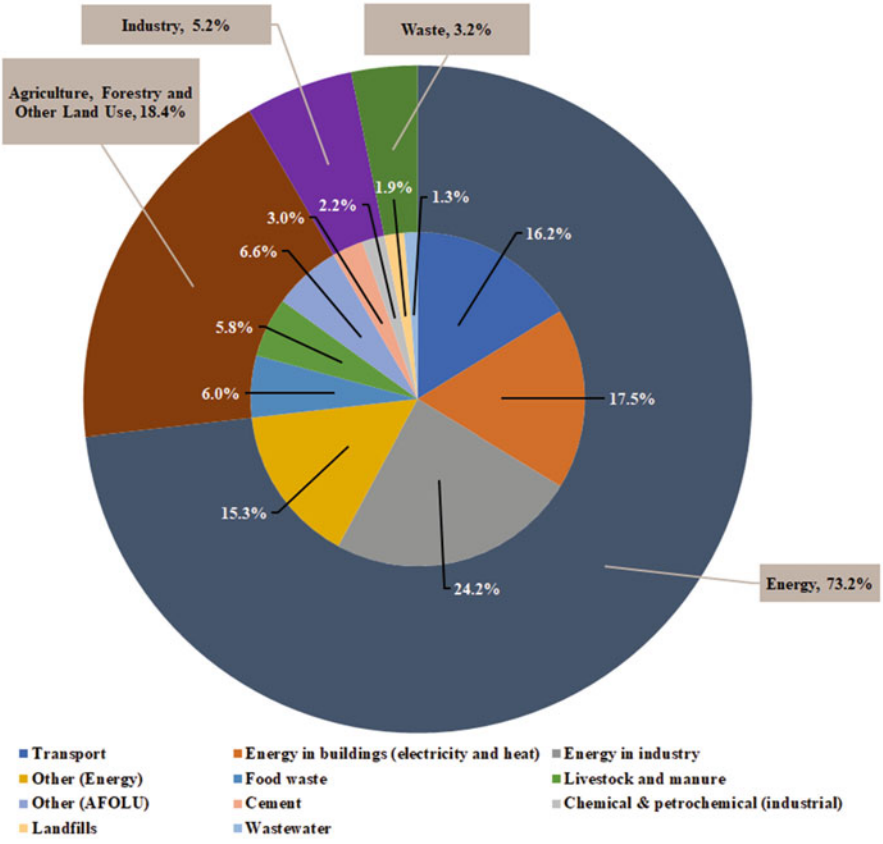


Fig. 1 Percentage of global greenhouse gases emitted by various sectors (energy, waste, industry and agriculture, forestry, and other land use) in 2016 (IPCC 2014; Ritchie and Roser 2020)

are broken down into smaller molecules such as sugars, lipids, and amino acids through the process of hydrolysis by hydrolytic microorganisms. The products of hydrolysis are further converted to intermediate products such as volatile fatty acids and alcohols during acidogenesis (stage 2) by acidogenic microorganisms. Thereafter, acetate-forming (acetogenic) and hydrogen-forming microorganisms convert the intermediate products to acetate, hydrogen (H_2), and CO_2 during acetogenesis (stage 3). In the final stage, acetate is converted to CH_4 and CO_2 through acetoclastic methanogenesis, while H_2 and CO_2 are utilized for the production of CH_4 via hydrogenotrophic methanogenesis both involving methanogenic microorganisms that thrive under low oxygen conditions. Methane, which is approximately 60–70% in biogas, produced from the anaerobic digestion process can be used as an alternative energy source for heating and electricity. Approximately 80% of GHGs emitted into the atmosphere can be lowered when biogas is used as an alternative energy source to conventional natural gas and fossil fuel-derived energy (Arif et al. 2018). Additionally, another product of the anaerobic digestion process,

digestate, can be harnessed as a nutrient-rich alternative to chemical/mineral fertilizers when properly managed, further reducing GHG emissions associated with chemical fertilizer production. A recent life cycle assessment study by Nordahl et al. (2020) indicated that landfilling potentially emits about 400 kg CO_{2e} per ton of organic waste, while composting and upgrading biogas produced via dry anaerobic digestion of raw organic waste to renewable natural gas reduced emissions by 41 and 2 to 36 kg CO_{2e} per ton of organic waste, respectively. The conventional linear approach to waste management, which involves open dumping, burning, or landfilling of organic and industrial waste, is unsustainable and further exacerbates the negative effects of climate change. On the other hand, the anaerobic digestion circular approach aims to valorize organic waste by converting it to methane and digestate. Valorization of untapped organic waste streams for biogas and digestate production may aid in climate change mitigation by applying the anaerobic digestion circular approach to reduce GHG emissions compared to conventional linear approaches (Fig. 2).

Waste Valorization Through Anaerobic Digestion

Waste production by human activities has been exacerbated by urbanization (Bhada-Tata and Hoornweg 2016). Waste accumulation and poor waste management impact negatively the environment resulting in concomitant adverse climate change effects.

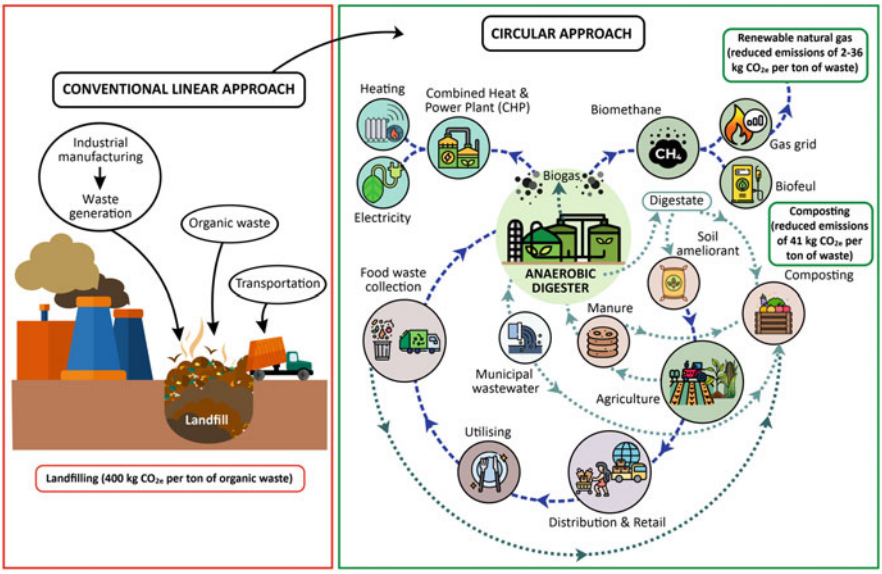


Fig. 2 Potential greenhouse gas emissions by landfilling as a conventional linear approach and anaerobic digestion (AD) as a circular approach for organic waste management (Adapted from Nordahl et al. (2020) and Kakadellis et al. (2022))

Governments around the world are faced with issues of waste management and climate change and are exploring different environmentally friendly waste management strategies in an attempt to mitigate environmental catastrophes and climate change effects. Unprecedented changes in the climate system could adversely affect agricultural yield in the next century (Misra 2014). Waste valorization to biogas addresses these issues by making use of organic waste streams such as municipal wastewater, as well as agricultural waste, which comprises food and animal waste.

Valorization of Animal Manure

The agriculture, forestry, and other land use sector is a major contributor to climate change as it accounts for about 18.4% of global GHG emissions (Ritchie and Roser 2020). Agricultural industries are known to produce a large amount of biomass, which is a suitable substrate for bio-economy due to its high carbon content (Rao and Rathod 2019; Duque-Acevedo et al. 2020). The increased processing of agricultural products (such as livestock products) due to increased demand by the ever-growing global population has resulted in the rapid generation of animal wastes. One of the main sources of pollution in the livestock industry is the storage and disposal of animal waste, which can be a daunting task, as animal manure contains a wide array of microorganisms that are responsible for the production of CH_4 and other GHGs that are emitted into the atmosphere (Loyon 2018). Livestock and manure account for 5.8% of global GHG emissions, which form part of the GHG emissions by the agriculture, forestry, and other land use sector (Ritchie and Roser 2020). If not properly managed, the manure poses a public health concern as they degrade the environment and become a possible source of contamination and GHG emission.

Some developing countries resort to indiscriminate dumping and/or incineration of these animal wastes, which could potentially cause air, soil, and aquatic pollution (Weichenthal et al. 2017; Adejumo and Adebiyi 2020). The increasing quantity of animal waste produced is harder to control and has detrimental effects on climate change. Hence, there is a need to reduce the amount of animal waste produced. Animal waste can also be utilized as a potential substrate for the production of value-added products (Rao and Rathod 2019). Animal manure comprises waste products from domesticated animals, which could be in solid, slurry, or liquid form (Liu and Wang 2020). Besides their extensive quantity of microbial entities, this waste product is rich in organic matter and fiber (Siles et al. 2016). In addition to their high content of macronutrients, which includes nitrogen, phosphorus, and potassium, animal manure contains micronutrients such as copper, nickel, manganese, zinc, and iron (Shen et al. 2015).

Classification of animal manure is based on the type of animal. Ruminants are the biggest contributors to GHG emissions through enteric fermentation, which is an essential part of their digestive system. During enteric fermentation, a significant amount of CH_4 and CO_2 is released from the rumen into the environment via eructation or belching (Grossi et al. 2019). Emissions from ruminants such as cattle, goats, sheep, and buffaloes are mostly CH_4 (>90%) resulting from the digestion of

ingested feed via enteric fermentation. Birds and monogastric animals such as pigs and horses that do not undergo enteric fermentation as part of their digestive processes emit most of their CH_4 through their manure (Ripple et al. 2014).

Conventional Management of Animal Manure

Smallholder farmers in sub-Saharan Africa have always used animal manure to promote crop production (Ndambi et al. 2019). Disposal of animal manure in aquatic bodies affects biodiversity as the decomposition of the organic matter content of animal manure leads to the depletion of dissolved oxygen levels of aquatic ecosystems. This poses a threat to aquatic organisms that require oxygen for survival (Daniel et al. 1993; Neshat et al. 2017). This disposal method also poses the threat of GHG emissions. Indiscriminate dumping of animal manure in landfills is not feasible due to soil and groundwater contamination by pathogenic microorganisms and organic matter (Neshat et al. 2017).

Conventional means of valorizing animal manure are via direct application as an organic fertilizer, i.e., land spreading and storage mostly for agronomic purposes. Application of some animal manure, such as poultry manure, has the potential to burn plants if utilized directly as a soil ameliorant to enhance plant growth, without any form of treatment, due to its high nitrogen content (Babaee et al. 2013). There is also a possible risk of volatilization of essential nutrient portions of the animal manure, environmental contamination, and potential GHG emissions during land spreading and storage of animal manure (Loyon 2018). Animal manure can also be incinerated to serve as fuel or composted to degrade organic matter and generate a potential soil conditioner. Mitigation of hurdles associated with the production and processing of animal manure is challenging considering the global need for livestock products. Some systems have been put in place to mitigate the possible challenges of GHG emissions from animal manure. These systems include modification of the animal's feeding needs by the incorporation of some feed additives to influence the manure composition and quantity, investing in manure protective covers to avert escape of CH_4 from manure under storage, and composting of animal manure (Hoque et al. 2022). However, the incorporation of productive and eco-friendly strategies such as anaerobic digestion into its management could lead to a reduction in GHG emissions. For example, in 2020, the United States of America reduced GHG emissions by approximately 5.29 million metric tons of CO_2 equivalent by implementing manure-based anaerobic digesters (EPA 2021).

Anaerobic Digestion of Animal Manure

The utilization of animal manure for the production of biogas and potential soil ameliorant via the metabolic process of anaerobic digestion is a sustainable and ideal means of managing this waste. Animal manure is rich in nitrogen and poses the risk of ammonia inhibition or possibly digester failure during anaerobic digestion, hence the need to include low nitrogen content co-substrates such as lignocellulosic wastes (Li et al. 2018). Recent advances in biotechnology have led to the development of different strategies for addressing the challenges of ammonia inhibition to enhance the metabolic process of anaerobic digestion of animal manure for optimal

production of biogas and digestate. Such strategies include the introduction of active microbial strains to improve the inhibited stages of anaerobic digestion (bioaugmentation) and the utilization of nanomaterials to enhance biogas production (nanotechnology), among others (Roopnarain et al. 2021). In addition to reducing the potential GHG emissions from animal manure, anaerobic digestion is a means of odor control and enhances the quality and biosafety of animal manure when the by-product, digestate, is utilized as a soil ameliorant to promote plant growth.

Valorization of Municipal Sewage Waste through Anaerobic Digestion

Municipal sewage or municipal wastewater comprises used or polluted water discharged from sanitation facilities in residential, commercial, institutional, and public facilities including restaurants, schools, hospitals, and prisons (EPA 2012; Mouele et al. 2015). Wastewater produced from these facilities can be categorized as blackwater and greywater (Tilley 2014). Blackwater is mainly wastewater from toilets and contains human excreta, urine, and the related sludge, while greywater represents other waste streams originating from bath, shower, sinks, kitchen, and laundry, which usually contain cleaning chemicals, soap, fat, and oil (Fig. 3) (Tilley 2014). Therefore, municipal sewage is a complex mixture of human waste combined with biological contaminants such as pathogenic microbial agents and chemical pollutants, representing a potential hazard to human health (García-Aljaro et al. 2019). Consequently, there is a greater need for appropriate wastewater treatment technologies that can handle the complex mixture of compounds associated with municipal wastewater. These strategies should not only reduce sanitation problems but also mitigate possible GHG emissions, thereby protecting human health and lessening climate change risk.

Generally, CO_2, CH_4, and N_2O are the major GHGs emanating from the wastewater sector during the treatment process (Hua et al. 2022). The release of these gases to the environment could be through direct emissions mainly related to biological waste decomposition in sewers and at wastewater treatment plants during wastewater and sludge treatment or indirectly due to energy consumption (Chen and Kuo 2016). Direct emissions are majorly attributed to uncontrolled biological processes including CH_4 production from the decomposition of organic matter during anaerobic digestion (Mannina et al. 2016); CO_2 emissions from microbial respiration and N_2O emissions as a consequence of biological nitrogen removal during denitrification and nitrification (Massara et al. 2017). Biological degradation of organic matter during wastewater processing accounts for approximately 1.3% of global GHGs (Ritchie and Roser 2020). Indirect emissions of GHGs are mainly due to energy and material consumption during the treatment process and are recognized as an important source of GHGs (Mamais et al. 2015). More specifically, carbon emissions associated with electricity consumption during production processes are indirect emissions generated from sewage treatment plants (Lin 2020). Globally, wastewater treatment plants use about 3–5% of electricity during the operation of

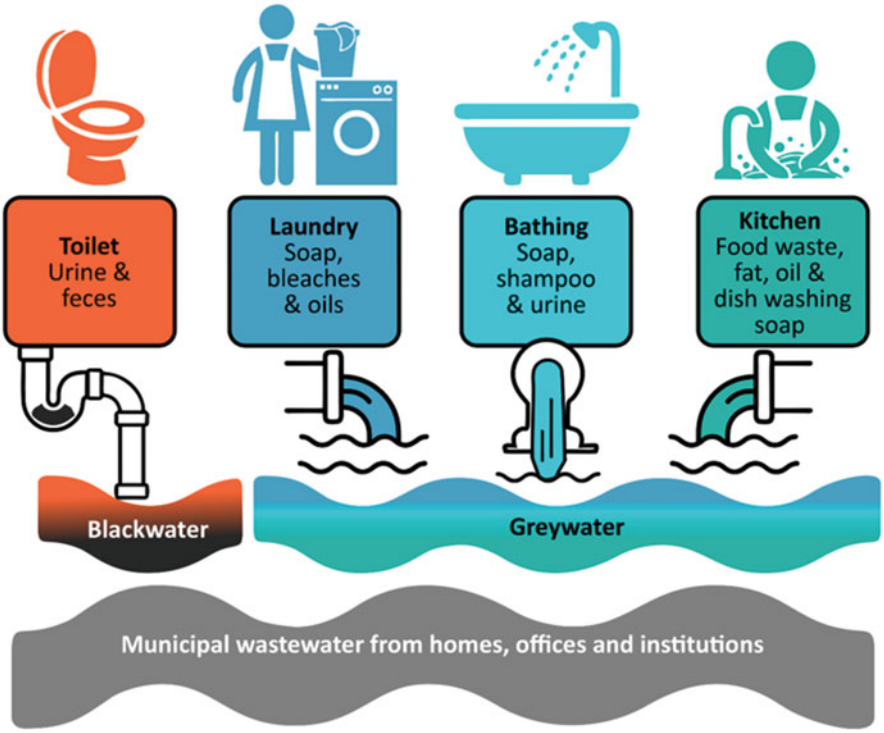


Fig. 3 Municipal wastewater sources and their constituents

sewage treatment plants, blowers, water pumps, aerators, and other equipment. Aeration and sludge treatment are the main energy-intensive processes, which account for 50–60% and 15–25% of the total energy consumed by wastewater treatment plants, respectively (Mamais et al. 2015).

The wastewater sector contributes to global warming and climate change, as it accounts for 56% of GHG emissions from the water industry and is responsible for an estimated 1.3% of global GHG emissions (Ainger et al. 2009; Ritchie and Roser 2020). In comparison with other sources of GHGs, the global contribution from this sector seems relatively small; however, recent research indicated otherwise, claiming that these estimates could be an underestimation (Tseng et al. 2016). Generally, CO_2 emissions from wastewater are major of two origins: biological and fossil. However, in the Intergovernmental Panel on Climate Change (IPCC) guidelines, CO_2 emissions from wastewater treatment plants are traditionally appended to biological origin, while emissions attributable to the carbon of fossil origin in wastewater remained unaccounted for (IPCC 2006). Conversely, with the use of radiocarbon data, Tseng et al. (2016) revealed the prevalence and possible contribution of fossil carbon that originated from petrochemicals in personal care products and synthetic detergents in wastewater. Accounting for this carbon of fossil origin increased estimated emissions from the wastewater sector by 23%.

Population growth and accelerated urbanization, particularly growth in low-income and middle-income regions, drive global wastewater GHG emissions upward (EPA 2012; World population review 2022). For example, between 1990 and 2020, the world population increased by up to 46%, but the highest growth rate was in less developed countries, accounting for 80% of the global population growth, and the trend is likely to continue (World Population Review 2022). In developing countries, the population increase has placed significant demand on existing wastewater treatment plants such that sanitation facilities cannot keep up with the rapid urban growth and its associated growing wastewater (Naidoo and Olaniran 2014). As such, only a small portion of wastewater produced by the sewer community is treated and most wastewater treatment plants do not undergo tertiary and sludge processing before disposal (Herbig 2019). Furthermore, most sewers and sludge treatment facilities in these regions are obsolete and non-functional due to insufficient funding to maintain pre-existing infrastructure and construct new sanitation infrastructure (Herbig 2019). Consequently, the discharge of raw or partially treated wastewater is common practice in most of these regions, which contributes to GHG emissions from the sector (Herbig 2019). Moreover, the common use of less advanced and onsite sanitation technologies including latrines, septic tanks, and open sewers provides an anaerobic environment that facilitates substantial GHG emissions (Reid et al. 2014; Huynh et al. 2021).

By contrast, most developed countries have well-functioning wastewater collection and treatment infrastructures that depend on centralized aerobic wastewater treatment technology (Koutsou et al. 2018). Emissions from such systems are negligible and incidental, but large amounts of biosolids are also produced that can result in high rates of CH_4 emissions (Koutsou et al. 2018). Furthermore, these regions also have strict regulations such as the secondary treatment standards in the USA and the Environmental Agency in England, which govern wastewater treatment and disposal by limiting the amount of organic matter that can be processed and encouraging the maintenance of environmental quality (EPA 2012). Thus, emission inequality between the developed and underdeveloped regions could be related to the described disparity in wastewater management among the different regions. For many least-developed countries, there is an urgent need to scale up sanitation for rapid urbanization; nevertheless, the emissions potential of the technology of choice should be considered.

The wastewater treatment sector can greatly contribute to emissions mitigation and circular sustainability by integrating energy production and resource recovery in wastewater management (Neczaj and Grosser 2018). Traditionally, urban wastewater management systems are linear treatment systems that primarily aim to meet effluent standards for disposal (USGS 2018). This approach needs to be converted into a sustainable, closed-loop urban wastewater management system that is based on the conservation of water and nutrient resources and climate change abatement (Faragò et al. 2021). Recently, municipal wastewater and sludge have been increasingly considered valuable resources containing water, nutrients, organic matter, and energy that can be recycled for various economic, environmental, and social benefits (Faragò et al. 2021). One of the benefits of adopting circular economy principles in

wastewater treatment is that resource recovery and reuse can provide economic savings and make the process self-sustaining, improving the economy (Neczaj and Grosser 2018). Additionally, with a careful selection of technologies particularly those that promote GHG recycling and utilization, emissions from the wastewater sector could be reduced (Ma et al. 2015). At present, the reduction in carbon and energy footprint is of worldwide concern for global warming mitigation and adaptation, and implementation of energy-sustainable technologies such as anaerobic digestion could play a role in GHG reduction (Faragò et al. 2021).

The majority of wastewater management systems used in most developing nations store untreated wastewater in open sewers, pits, and latrines, allowing the organic matter in them to decompose naturally, which releases the potent GHG CH_4 into the atmosphere (Shaw et al. 2021). On the contrary, an anaerobic digestion system feeds organic materials such as wastewater into a closed digester that allows microbial degradation of organic matter in the absence of oxygen (Roopnarain et al. 2021). Accordingly, GHGs generated during the anaerobic digestion process that might have been released through other treatment strategies are captured, indicating the potential of anaerobic digestion technology to reduce GHG emissions and associated climate impact (Bracmort 2010). Additionally, the anaerobic digestion of wastewater or wastewater sludge is beneficial for the production of energy-rich biogas that can be utilized as a renewable energy source (Korbag et al. 2020). Biogas generated during anaerobic digestion contains a high calorific value and heat energy; therefore, it can produce large amounts of electrical energy. Thus, biogas could be used during wastewater treatment to produce electricity, fuel, or heat onsite or fed into a district heating grid in place of fossil fuels (Korbag et al. 2020). Integration of anaerobic digestion into wastewater treatment plants has the potential to produce renewable energy, which can supplement or replace fossil fuels and reduce emissions related to energy consumption.

Food Waste Valorization Through Anaerobic Digestion

Globally, more than 1.3 billion tons of food waste is generated annually (Gustafsson et al. 2013; Arancon et al. 2017). In fact, a third of the total food produced for human consumption is lost or wasted globally. This accounts for not 6% of global annual GHG emissions (Scialabba et al. 2013). Food waste is generated during all stages of the food supply chain, from agricultural production to harvesting and post-harvesting. It is also generated during industrial processing and in the course of wholesale and retail activities. Food wastage is still evident in the food service sector, as well as with consumers (Turon et al. 2014). Energy consumed for wasted food production could have been channeled into other production, while concomitant emissions from the processes could have been averted. Food waste, traditionally disposed of via landfill and incineration, results in unsatisfactory effects such as generation of toxic (and often greenhouse) gases, fire incidents, bad odors, high energy input, and slow reaction kinetics; hence, valorization strategies are necessary (Zhang et al. 2014; Arancon et al. 2017; Gao et al. 2017). Although many landfills

employ gas capture, the efficiency is not optimal, and it is estimated at about 68% (Gregory et al. 2014). Food waste disposal by landfilling was shown to contribute 10 times more to climate change than other forms of food waste disposal strategies investigated, including incineration, composting, and heat-moisture reaction while anaerobic digestion contributed the least. There is also the danger of leachate from improperly sealed landfills (Gao et al. 2017). On its part, incineration of high-moisture food waste causes the release of dioxins. Generally, food waste incineration causes the emission of GHGs and destroys all potential for nutrient recovery or reuse (Paritosh et al. 2017; Slorach et al. 2019). All these indirectly exacerbate climate change effects. In order to secure a future for the planet, all endeavors should be underpinned by a drive to not contribute GHGs to the environment. Food wastes should therefore be diverted from landfills and incineration sites.

Measures for more effective food waste management by anaerobic digestion to mitigate climate change effects should include increased awareness of source separation of food waste from other forms of organic waste. This collection should be along the food supply chain (agricultural sector, industrial processing, wholesale/retail sector), food service sector, and from households. The measures should also provide incentives for collected or deposited food wastes and facilitate collection arrangements and easy access to centralized anaerobic digestion centers or localized anaerobic digestion units in order to reduce transportation costs (Roopnarain and Adeleke 2017; Slorach et al. 2019). Utilization of food waste as energy sources in such processes as anaerobic digestion should be areas of urgent priority research focus.

Exploring different waste valorization strategies therefore becomes imperative, and anaerobic digestion comes as a sustainable waste valorization strategy. Anaerobic digestion of food waste streams offers a viable substrate for the production of biogas and high-quality soil ameliorant and prevents the emission of CH_4 from landfills and incineration sites where organic waste would have invariably been deposited (Evans et al. 2009). When managed reasonably and effectively, food waste is a valuable resource in bioprocesses, producing reduced environmental effects. Food waste is high in moisture content and can be easily degraded. It also contains organic matter required by anaerobic digestion microbes, making it a good substrate for the anaerobic digestion process (Zhang et al. 2014).

A recent case evaluation by Gao et al. (2017) recommended anaerobic digestion as a promising food waste management strategy that contributes minimally to negative climate change effects and to acidification and eutrophication. Eriksson et al. (2015) also assessed GHG emissions from different food waste management scenarios from supermarkets in Uppsala, Sweden. The life cycle assessment of a kilogram of five food products (banana, lettuce, grilled chicken, beef, and bread) treated as individual waste streams was conducted. Of all the six different waste management strategies (landfill, incineration, composting, anaerobic digestion, animal feed, and donation), the greatest potential for reducing the emission of GHGs by 13 to 610 kg CO_{2e} per ton of food waste was found in the anaerobic digestion strategy, although variations existed among different food waste streams. An assessment of GHGs from different food waste management strategies cannot be

exhaustive because multiple factors have to be considered. Life cycle assessments incorporating all the factors tend to be holistic and are thus used in such assessments.

Application of Digestate from Anaerobic Digestion for Reduction in Greenhouse Gas Emissions

Digestate can be employed in different sustainable applications such as microalgal cultivation; biocontrol of plant pathogenic pests and fungi; seed pretreatment; and irrigation and livestock management. Recycling digestate as a substrate or inoculum in different bioprocesses for energy production is another sustainable means of its valorization (Roopnarain et al. 2022). Additionally, essential nutrients can be recovered and recycled from digestate for commercialization and for use as a soil ameliorant (Zhao et al. 2014; Nagarajan et al. 2019). Climate change effects including land degradation and desertification are predicted to decrease farmable land area due to soil erosion and nutrient loss (Evans et al. 2009; Arneth et al. 2019). Furthermore, the constant application of inorganic fertilizers to enhance crop productivity has been recorded to have adverse environmental effects such as land degradation, groundwater pollution, and possible soil infertility (Raimi et al. 2021). Composting is a conventional method of organic waste management, which involves the decomposition of organic waste under aerobic conditions (higher oxygen levels) to produce fertilizer. The composting process releases GHGs similarly to anaerobic digestion; however, there is much variability in the amount of emissions produced by each process. According to the report by Walling and Vaneeckhaute (2020), the amount of GHGs emitted by composting and anaerobic digestion are predominantly affected by factors such as feedstock and the type of operations available in different countries. Anaerobic digestion provides a sustainable treatment option for organic waste management through stabilization, sanitation, and nutrient recycling similar to the conventional method of composting (Möller 2015); however, it also harnesses CH_4 as an energy source. Utilizing digestate in place of inorganic fertilizers as a land management strategy could lead to environmental sustainability and reduce human impacts on other current global challenges such as soil and water pollution (Seruga et al. 2020). Moreover, GHG emissions from digestate are much lower than raw organic waste due to the reduction in CH_4 potential of the original organic waste after anaerobic digestion, particularly in comparison with untreated manure (Paolini et al. 2018).

A drawback to digestate use for land application includes leaching of nitrates and volatilization of nitrogen as ammonia or N_2O, which can negatively affect the environment (Paolini et al. 2018). Therefore, it is pertinent that post-treatment of digestate is conducted prior to land application to prevent further GHG emissions as well as to meet certain regulatory, safety, and hygiene standards. Examples of post-treatment include separation of liquid and solid digestate, pasteurization, drying, composting, struvite precipitation, ammonium stripping/recovery, and evaporation (Törnwall et al. 2017; Logan and Visvanathan 2019; Roopnarain et al. 2022). Inadequate handling of digestate could lead to its reduced efficiency as a soil

ameliorant as possible loss of essential macronutrients through volatilization is imminent and preventive methods should be implemented for mitigation. Volatilization usually occurs during the storage and transportation of digestate. Despite CH_4 production during anaerobic digestion, there is a possibility of CH_4 and CO_2 emission from digestate under storage; this results from the decomposition of undigested organic material following anaerobic digestion. However, extending the anaerobic digestion period without feeding digesters until the most organic matter is mineralized and/or appropriate aeration of digestate in storage to enhance the aerobic metabolic pathway are possible means of alleviating this challenge (Gerber et al. 2013). Designing anaerobic digesters with low leakage and high-quality gas-tight technology for storage may also mitigate GHG emissions (Walling and Vaneeckhaute 2020; Liebetrau et al. 2021). Furthermore, Johnston and Bruulsema (2014) and Snyder et al. (2009) provided recommendations on best practices in applying fertilizers in terms of rate, timing, area, and source of fertilizer to improve nutrient use efficiency and prevent unnecessary GHG emissions.

Anaerobic digestion promotes nutrient recovery from animal manure, municipal wastewater, sewage sludge, and food waste by conserving and mineralizing organic matter into more soluble and biologically available forms. Important plant nutrients such as macronutrients (N, P, and K) and micronutrients (B, Fe, and Mn), as well as undigested organic matter, accumulate during anaerobic digestion (Adeleke et al. 2019; Nkuna et al. 2021). Animal manure digestate is a potential soil ameliorant for soil fertility enhancement and plant growth promotion due to its high concentration of beneficial microorganisms that are potential plant growth-promoting agents besides the high content of nutrients (Walsh et al. 2018; Adeleke et al. 2019). Digestate application as a soil fertility enhancer impacts climate change via reduction of CO_2 emission as it also encourages soil carbon sequestration (Béghin-Tanneau et al. 2019; Hoque et al. 2022). Beneficial microorganisms that support plant growth and development are known as plant growth-promoting microorganisms (PGPMs) and their application to enhance plant growth is dependent not only on their ability to acclimatize, but also on their ability to colonize and thrive among indigenous rhizosphere microbiomes. Enhancing plants' tolerance to environmental stress such as salinity and drought is a mitigation strategy of PGPM application to combat climate change (Zytynska et al. 2020; Fiodor et al. 2021).

Additionally, sewage sludge and wastewater digestate present valuable sources of nutrient-rich organic soil ameliorant for crop production (Eid et al. 2019). The use of wastewater sludge as a bio-based alternative to synthetic fertilizers provides the indirect reduction in emissions through reduced dependency on fossil-based mineral fertilizers (Ding et al. 2021). However, sewage sludge produced in wastewater treatment processes carries not only nutrients but also hazardous organic and inorganic pollutants as well as pathogenic microorganisms, which must be considered before application (Kirchmann et al. 2017; Goberna et al. 2018). Sludge treatment technologies including composting, thermophilic anaerobic digestion, thermal drying, and lime treatment are required to achieve higher pathogen removal and enable agricultural reuse of sewage sludge (Kelessidis and Stasinakis 2012). Moreover, sludge stabilization techniques, particularly anaerobic digestion, have been shown to

make sewage sludge more stable during storage and provide emissions reduction when applied to agricultural land (Yoshida et al. 2015). Food waste digestate, similar to municipal sewage, may contain pathogenic microbes and requires proper management to meet good quality digestate standards before use. Examples of management treatment options include heat treatment at 70 °C for 60 minutes prior to digestion and/or thermophilic anaerobic digestion with composting (Banks et al. 2018). Food waste digestate may augment fertilizer input and subvert energy and GHG emissions that would have been required for that purpose. Although the land application of municipal sewage and food waste digestate results in biogenic emissions of CO_2 and N_2O, its application as soil ameliorant potentially reduces net GHG emissions by 11 kg CO_{2e} per ton of digestate if manufactured N and P fertilizers were to be replaced by the digestate compared to landfilling digestate, which can result in GHG emissions of 190 kg CO_{2e} per ton digestate (Peng and Pivato 2019). In another study, Song et al. (2021) reported that composting food waste digestate with sawdust and mature compost reduced NH_3 volatilization by 83%. These studies suggest that the digestate resulting from the anaerobic digestion process can potentially serve as a mitigation strategy for climate change when applied as a soil ameliorant.

Conclusion

This chapter highlights the potential of anaerobic digestion technology in creating a circular approach by redirecting organic waste from landfills and water streams to anaerobic digesters. Furthermore, an overview of how different organic waste streams contribute to global GHG emissions is provided. Applying anaerobic digestion technology can potentially valorize large amounts of organic wastes through microbial conversion to renewable energy for electricity generation and soil ameliorant for crop production while reducing the net emission of GHGs. However, further research on refining this circular approach for improved efficiency and economic feasibility is required, especially when considering factors such as transportation, infrastructure, fossil fuel energy inputs, indirect emissions, digestate post-treatment processes, and eutrophication. Furthermore, there is a need for studies to determine an estimate on the amount of global greenhouse gas emissions that can be reduced using anaerobic digestion technology for each type of organic waste. Practicing nutrient use efficiency techniques during the application of digestate that meets standard requirements as a soil ameliorant is recommended to improve agricultural sustainability and mitigate GHG emissions associated with inorganic fertilizer production and land application. This approach can possibly alleviate the potential problems of waste management and energy and food insecurity to sustain the ever-increasing global population needs and mitigate climate change effects.

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