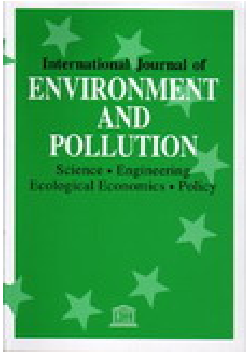


International Journal of Environment and Pollution

ISSN online: 1741-5101 - ISSN print: 0957-4352
https://www.inderscience.com/ijep

A review of the current situation of municipal solid waste management in India and its potential for anaerobic digestion

Rikitha S. Fernandes, Nitinkumar S. Shetty, B.H.S. Thimmappa

DOI: 10.1504/IJEP.2021.10050199

Article History:

Received:	14 January 2021
Last revised:	28 August 2021
Accepted:	12 April 2022
Published online:	01 September 2022

A review of the current situation of municipal solid waste management in India and its potential for anaerobic digestion

Rikitha S. Fernandes, Nitinkumar S. Shetty* and B.H.S. Thimmappa

Department of Chemistry,
Manipal Institute of Technology,
Manipal Academy of Higher Education,
Manipal – 576104, Karnataka, India
Email: rikkifernandes@gmail.com
Email: nitin.shetty@manipal.edu
Email: bhs.thims@manipal.edu
*Corresponding author

Abstract: This work aims to give an overview of the current situation of municipal solid waste management (MSWM) in India to discuss the consequences of untreated waste for humans and the environment, and to show the potential for sustainable disposal. In particular, anaerobic digestion has been discussed, as this technology is already being widely used in India and proves its sustainable effect. The high organic fraction content in MSW makes it suitable for anaerobic digestion and can be used sustainably. Besides, waste-to-energy (WTE) technology is very profitable due to biogas production out of organic waste and the generation of fertiliser out of the slurry. The result of this analysis on the current situation and prospects shows that India's biogas production is lower than its potential. This aspect is mainly due to non-functioning waste management, including separation, collection, and transport.

Keywords: biogas; biomethanation; biowaste; organic manure; waste-to-energy conversion; waste management; organic waste; sustainable development; landfills; anaerobic digestion.

Reference to this paper should be made as follows: Fernandes, R.S., Shetty, N.S. and Thimmappa, B.H.S. (2021) 'A review of the current situation of municipal solid waste management in India and its potential for anaerobic digestion', *Int. J. Environment and Pollution*, Vol. 69, Nos. 1/2, pp.130–150.

Biographical notes: Rikitha S. Fernandes is a student, studying MSc Chemistry at Manipal Institute of Technology, MAHE, Manipal.

Nitinkumar S. Shetty is a Senior Assistant Professor at Manipal Institute of Technology, MAHE, Manipal. He is basically an organic chemist with MSc and PhD in Chemistry and MBA in Environmental Management.

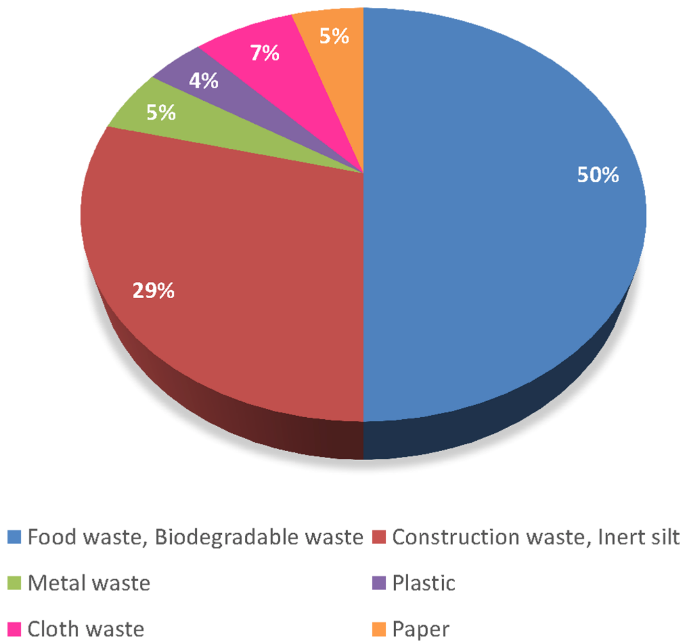
B.H.S. Thimmappa is a Professor of Chemistry at Manipal Institute of Technology, MAHE, Manipal. He has pursued his PhD from IIT Bombay and later went for his post-doc studies in the USA.

1 Introduction

India's population is growing quite rapidly compared to other countries, and hence, the amount of municipal solid waste (MSW) increases day by day (Sharma and Jain, 2019). The demand for energy among various sectors increases substantially with the increase in population. Due to insufficient recycling and treatment of solid waste, the health risk to humans and the pollution of the environment also increases. Hence, municipal solid waste management (MSWM) is a crucial element of sustainable metropolitan development. Humans create waste, out of which 72% of the waste is dumped, which is mostly untreated and uncontrolled and hence could be a threat to human health and the environment. Besides, landfilling and incineration are not considered to be absolute solutions to this issue. This waste consists of 50–60% biodegradable substances, which today could be easily treated with various waste-to-energy (WTE) technologies (Figure 1) and WTE could be employed instead of using fossil materials, since they produce energy out of waste, minimise waste and protect the environment. The country needs three or four times the energy consumed today to reach the energy requirement. Therefore, biogas technology is one of the significant WTE options which are already operating and has much potential to meet the energy requirement. Biogas can replace about 30% of the energy supplied by conventional fuels such as firewood. The environmental problems such as CO_2 and CH_4 release, indoor air contamination, and organic pollution can be reduced with biogas. Further, the installation and maintenance of functional biogas plants will bring employment opportunities to many youngsters and secure the way into economic waste recycling (Dhar et al., 2017).

Although many strategies have been put forward by the government, SWM-related problems are still unresolved and hence this paper focuses on the challenges of MSWM in India and its consequences. Besides, it also accounts for efficient methods such as anaerobic digestion that can be taken into consideration to combat issues related to MSWM. Uncontrolled dumping of untreated waste endangers both the environment and humans and hence actions have already been taken by the government and non-governmental organisations (NGOs), but still, it needs to be set in motion. Special attention will be given to organic waste to show the potential and the methods with which biodegradable fractions can generate energy. Due to the high biodegradable content in MSW, a reduction of organic waste using appropriate WTE technologies would make sense to minimise the amount of MSW. The focus lies mainly on a method called anaerobic digestion (AD), as this has already been implemented several times and has already achieved success in India.

Figure 1 Waste composition of urban municipal solid waste (MSW) in typical Indian cities (see online version for colours)



Source: Ahluwalia and Patel (2018)

2 The challenge of waste management

As a consequence of rapid urbanisation and economic growth, the amount of solid waste grows and will reach about 300 million tons in 2047 (Swain et al., 2020), and the per capita of MSW generated daily ranges from about 200 gm. in small towns to 600 gm. in cities with a collection efficiency of 70% (Misal and Deshmukh, 2020). Central Pollution Control Board (CPCB) calculated the amount of MSW in 366 Indian cities and documented an increase from 47.3 metric tons (MT) in 2011 to 161 metric tons in 2041. Besides, approximately around 143,449 MT of MSW is being generated daily, out of which 111,000 MT and 35,602 MT are collected and treated respectively (Sunil Kumar et al., 2017). Waste generation in cities has been found to have notable variation in the waste per capita/day generation at an exponential rate (from 0.24 to 0.85) beginning from the year 2001 to 2018 as shown by the CPCB in their annual reports in 2018, which is anticipated to increase quickly in a short period (Sharma and Jain, 2019).

People in India migrate from villages to cities because of industrialisation, and it is anticipated that in the next 10 years, half of the Indian population will live in cities (Sharma and Jain, 2019). With this rapid, unplanned urbanisation, the MSWM system in India is complicated, undertaking, and combined with improper waste management practices (Ghosh, 2018). This complexity leads to pollution of air, water, or land, which consequently leads to long-term deterioration of productivity. In turn, this aspect can influence the economy due to the degradation of economic circumstances (Bharti et al., 2017). Other challenges faced in India are the inappropriate use of the waste collection to disposal methods and the limited availability of solid waste management professionals, and the lack of tactical solid waste management plans (Kumar et al., 2017). Furthermore, it has been observed that south Asian countries have low GDP per capita and generate fewer amounts of MSW consisting of a higher proportion of biodegradable waste (Shekdar, 2009) and highly dense Indian cities such as Mumbai, Delhi, Kolkata, Chennai, Bangalore, Hyderabad contribute to a higher amount of solid waste generation, which comprises of 70-80% of the total waste produced per day in India (Energy and Forward, 2010).

The rapid growth of MSW in cities is shown in the following table (Table 1).

Table 1 Waste generation of selected metro-cities in India

City	*Population (2011) [Million]*	*Waste Generation [MT/Day]*	
		1999–2000	*2015–2016*
Mumbai	12.4	5355	11000
Delhi	11.0	400	8700
Bangalore	8.4	200	3700
Chennai	7.1	3124	5000
Hyderabad	6.7	1566	4000
Ahmedabad	5.6	1683	2500
Kolkata	4.5	3692	4000
Surat	4.5	900	1680
Pune	3.1	700	1600
Jaipur	3.0	580	1000
Lucknow	2.8	1010	1200
Kanpur	2.8	1200	1500
Nagpur	2.4	443	1000
Visakhapatnam	2.0	300	350
Indore	2.0	350	850

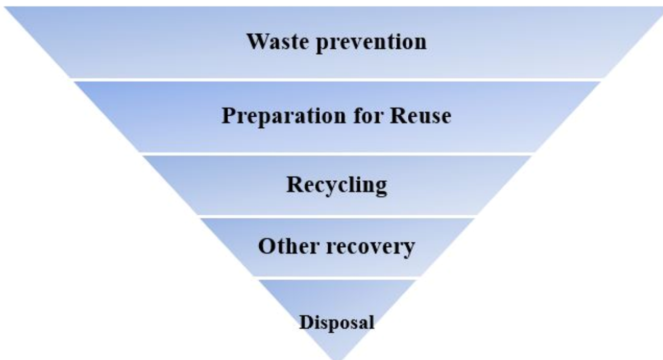
Source: Data from Central Pollution Control Board (CPCB)

The definition of MSW is defined by Solid Waste Management Rules 2016 and includes waste from households, commercials, markets, slaughterhouses, institutions like schools and community halls, horticulture like parks and gardens, road sweeping, biomedical institutions, and sludge from drainage (Ahluwalia and Patel, 2018). The solid waste management rules regulate MSWM in India, e.g., collection, transportation, and treatment (Sharma and Jain, 2019). For effective treatment, it is necessary to divide the waste into three different streams based on identifiable waste containers, particularly biodegradable, non-biodegradable, and domestic hazardous waste. Therefore 60–70% of the money goes to waste collection, 20–30% to transportation, but inadequate transportation and poor collection are challenging to MSWM. Urban local bodies (ULB) delegated by the state government do not have adequate resources and the capacity to implement the regulations for the solid waste rules (Dhar et al., 2017). This leads to uncontrolled dumping, which causes risks for humans and the environment. The Ministry of Urban Development (MUD) implemented a principle of waste minimisation called the 3R principles of reduce, reuse, and recycle. The implementation of this principle should be carried out with suitable collection containers, segregation of different groups of wastes and processing of the waste, and appropriate transport and disposal mechanisms. Above all, urban areas can thus guarantee the sustainable disposal of (MSW) (Dhar et al., 2017). Data shows that only 28% of the collected waste is treated, and 72% is disposed by landfilling without any precaution or operational control (Sharma and Jain, 2019). This operational deficiency clearly represents a malfunction in MSWM in India. Waste collection in bigger cities ranges between 70% and 95%, while in several smaller towns, it is below 50% (Sharma and Jain, 2019). Around 70% of Indian cities do not have sufficient capacity to transport the solid-waste, and sanitary landfills for adequate waste disposal are missing (Swain et al., 2020). MSWM is a challenging environmental issue. Uncontrolled dumping causes a lot of environmental problems because of emissions like CO_2 and CH_4. After carbon dioxide, methane, generated from the anaerobic decomposition of biodegradable waste, plays a huge part in global warming because it is worth 21 times more than carbon dioxide (Sharma and Jain, 2019).

In addition to the issue of emissions, the land area needed to dispose of the generated waste poses a problem. The dumping of waste in landfills affects the ground beneath due to leachate, contaminating the groundwater. Leachate, a consequence of decomposing biodegradable matter, releases nitrous oxide, which is 298 times higher than the global warming potential of carbon dioxide (Ahluwalia and Patel, 2018). Once landfill leachate contaminates water bodies, the result can be catastrophic and unpredictable. When underground water mixes with the water supplied to the aqua farms, all the toxic substances can move upwards in the food chain. The high level of heavy metal contamination makes leachate dangerous. Research shows that heavy metals such as arsenic, considered to be one of the most toxic elements of human life, are found in groundwater in increased amounts in many places. These heavy metals come from untreated waste and are potentially toxic to crops, animals, and humans because they quickly accumulate in vital organs and endanger crops, and later human health (Ghosh, 2018).

There are many ways to reduce the high amount of dumping, but the type of process to be used depends on solid waste compounds. Nowadays, there are a lot of technical options for the treatment of MSW, which can be categorised into four groups: aerobic digestion or composting, anaerobic digestion, incineration, and landfill. Among these treatment options, composting requires a vast area and takes a long time to be treated. Incineration releases toxic emissions and is not preferable due to the high biological content of MSW in India. In the waste hierarchy of Europe (Figure 2), a landfill is the last option and should be avoided as much as possible. Waste dumping is one of the most significant contributors to greenhouse gas (GHG) emissions. In many countries, especially in Europe, there are strict requirements for the disposal of waste. As far as economically and ecologically acceptable, they are following the waste hierarchy, which indicates in which order waste should be handled, starting with waste prevention, then preparation for reuse, recycling, recovery like WTE, and finally disposal. As a result, some countries have succeeded in reducing landfill waste to 20%. In India, a landfill is still the primary treatment. This system is due to poor political support, improper separation, inconsistent collection, and transportation (Logan and Visvanathan, 2019). The high percentage of biodegradable waste, high moisture content, and low calorific value is not suitable for incineration but favours biological treatments like composting and anaerobic digestion (Breitenmoser et al., 2018). If the organic content of MSW was used in composting plants or anaerobic digestion plants, the burden on landfills could be reduced by half (Ghosh, 2018). Relative to the facts described above, anaerobic digestion is the most effective and economical treatment in India. Not only can the waste be reduced, but also biogas and organic fertilisers can be recovered from the process (Logan and Visvanathan, 2019).

Figure 2 Waste hierarchy in Europe (see online version for colours)



The main categories of municipal waste in India are composed of biodegradable waste such as kitchen and food waste, composite wastes such as tetra-packs, inert waste matter such as construction and demolition waste, household hazardous wastes such as leftover paints, medicines, batteries, and recyclable matter such as bottles, etc. (Joshi and Ahmed, 2016). The composition of MSW is approximately 40–60% compostable, 30–50% inert, and 10–30% recyclable (Sharma and Jain, 2019). This low percentage of recyclables results from rag pickers who collect paper, glass, plastic, and metals to sell it to dealers. In turn, the traders sort the waste until they have enough material to sell it to the recycling industry. Some waste pickers collect recyclable waste through the door-to-door collection, others are searching for recyclables on dumped waste, sidewalks, and landfills, and endanger their health (Ahluwalia and Patel, 2018). In a way, they support waste recycling by bringing recyclables to further treatment. Though, in this way, operational waste management can never be built. Therefore, a regulated system with remuneration would have to be introduced that will lead to many positive impacts.

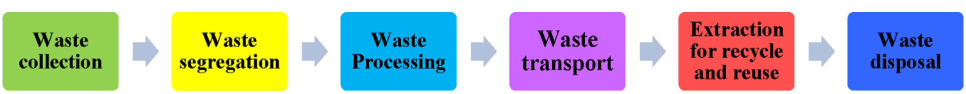
3 Methods

3.1 Collection of biodegradable waste

MSWM involves the control of waste generated, its storage, collection, transfer and transport, processing, and disposal in an appropriate manner that corresponds to the principles of public health, economics, engineering, conservation, aesthetics, public attitude, and other environmental contemplations (Ramachandra et al., 2018). Firstly, waste must be separated, collected, and transported. The following paragraphs concentrate on the potential of compostable waste and programs that already affect the collections. Beginning with a huge part in compostable waste, agricultural waste would secure much feedstock for further treatment. India produces around 98 million MT of rice and 130 million MT of rice straw. With these high volumes, India ranks second in rice production worldwide. About 50% of rice straw is used as food for animals, but the other half is thrown away together with other solid waste. Another significant contributor to agricultural waste is cane, with a production of 50 million MT of cane trash out of 350,000 MT of cane. Cane waste has no commercial use and thereby is entirely burned to reduce the volume. With the appropriate treatment like bio-methanation, cane waste can be used to produce energy. Other agricultural waste can also be used for WTE technology like cotton, pulse, sunflower, groundnut shells, and coconut trash. Farmers have different harvest seasons, and thus, vast quantities of biomass are burned instead of collected and used for producing energy (Dhar et al., 2017).

Large-scale composting plants do not fail because of process technology but because of non-uniformity in the entire collection system (Mani and Singh, 2016) which includes segregation, collection, and transportation. The main duty of the governmental organisations is to collect wastes from doorsteps, and it is done manually, and such tasks are handed over to other private organisations as well who take up the initiative to carry out the waste management process right from collection to final disposal (Figure 3). For a profitable plant, a constant waste stream must be guaranteed. Therefore, biodegradable waste must be segregated and distributed in decentralised plants like composting, which will reduce the extent of waste transportation. Further, the disposed waste will be minimised thereby reducing the risk of greenhouse gases and leachate. India has a high potential in terms of using biodegradable waste for composting or other WTE plants. To exploit this potential, the government, and organisations like ULB and panchayath raj institutions (PRI) must sensitise people and offer opportunities for cooperation. Solid Waste Management Rules 2016 were making segregation into biodegradable, non-biodegradable, and domestic hazardous waste. Surprisingly, the large metropolitan cities show the worst performance, though the waste collection should be natural there, e.g., Bengaluru and Pune have only around 50% of the waste segregated.

Figure 3 Workflow of SWM (see online version for colours)



Source: Mmereki (2018)

In comparison, mid-size cities like Mysore reach segregation of 95%, and in some small towns, even 100% (Ahluwalia and Patel, 2018). The major cause of this poor compliance is the shortage of resources, lack of internal management skills, inadequate funds, and human resources. Pune is a pioneer in garbage separation and directs a vision in which other cities must move to achieve a garbage separation, especially a continuous stream of biodegradable waste for composting. Since 1990 initiatives in Pune cooperate with waste pickers and offer them uniforms, equipment, identity cards, health insurance, and sheds for assembling recyclables from non-biodegradable waste. Rag pickers may sell the recyclables and keep the revenue. In return, it will be ensured that the separated wet waste will have proper treatment, such as composting in housing associations or delivery to nearby biogas plants (Ahluwalia and Patel, 2018).

3.2 Composting of organic waste

Composting is a biological process during which micro-organisms break down biodegradable substrates. There are two ways to decompose organic waste: aerobic and anaerobic digestion (Swain et al., 2020). Aerobic decomposition breaks down the organic matter into simpler compounds, thereby releasing carbon dioxide and water in the presence of oxygen. The quality of carbon present in organic waste drives the rate of decomposition. For instance, if carbon is present in a readily degradable form such as carbohydrates, the organic decomposition process will be accelerated. In contrast to it, a high amount of cellulose and lignin will decrease or slow down the rate of decomposition (de Araújo et al., 2010). The final product is called compost and can be used to nourish the soil or used as fertiliser. The compost also strengthens the ground as it becomes porous, and the roots can anchor themselves better. This aspect makes the soil more robust to pests and prevents rottenness (Ahluwalia and Patel, 2018). Being microbiological, the composting process is persuaded by the presence of carbonaceous and nitrogenous materials in the organic matter (Kumar, 2011).

Anaerobic decomposition converts the organic matter in the absence of oxygen into methane, which is a crucial component in biogas and liquid slurry which is a useful fertiliser. The slurry contains a substantial proportion of micronutrients and macronutrients and has a low amount of heavy metals than other synthetic fertilisers (Kumar et al., 2015). Biogas can be employed for small-scale domestic applications such as cooking, heating, and also for industrial large-scale applications in the production of electricity (Kleerebezem et al., 2015). Biogas is a sustainable source of energy and can be put to use instead of conventional fuels. With another treatment such as concentration, it can also be used to generate electricity using a generator (Ahluwalia and Patel, 2018).

Windrow composting, in-vessel composting, aerated static-pile composting, and vermicomposting are the different types of composting methods used in India (Pujara et al., 2019). The process of composting is quite economical and assists in reducing MSW, but the survival of micro-organisms under optimal environmental conditions remains a challenge. Since in most rural areas, wastes are collected in a mixed form comprising both organic and inorganic matter, the composting process seems to be difficult (Raje et al., 2001).

The most current WTE technology in India is anaerobic digestion (Dhar et al., 2017). It is a significant and viable technique for treating biodegradable matter present in MSW (Joshi and Ahmed, 2016). Anaerobic digestion of organic waste is a much more efficacious and practical option for the treatment of MSW in India than other biochemical treatment technologies in the aspects of waste to energy (Ghosh et al., 2017). It is an environmentally amicable process, and it can remarkably eradicate greenhouse gas emissions by utilising available resources compared to fossil fuels (Bharathiraja et al., 2018). Besides, composting requires more space than anaerobic digestion. Biowaste treatment by anaerobic digestion is the best approach for addressing the issues related to food waste disposal and organic waste, therefore, yielding beneficial outputs like biogas and fertilisers (Kougias and Angelidaki, 2018). The conventional anaerobic digesters use a single reactor for the biomethanation process and therefore do not require much space. Throughout the year, the warm climatic conditions, and the high availability of organic waste computes anaerobic digestion as an effective treatment of MSW. The resulting product after composting is used as non-odorous and pathogen-free fertiliser (Swain et al., 2020), and the use of digestate can reduce the demand for chemical fertilisers.

3.3 Anaerobic digestion process

Anaerobic digestion, also called biomethanation, is a series of biological processes (Kadam and Panwar, 2017) in which micro-organisms degrade organic substrates, for instance, biowaste, generating Biogas, and a nutrient-rich digestate in the absence of oxygen (Breitenmoser et al., 2018). It involves two different categories of micro-organisms, of which one comprises the acid-forming bacteria, and the other includes methanogens (methane-forming bacteria) (Rao and Maddaiah, 2010). This process is much slower than aerobic composting. Raw animal manure is already used in many places as fertiliser in agriculture and thus displaces chemical fertilisers. When the animal manure is anaerobically digested, the organic substrate is converted into Biogas, which is a renewable fuel, and digestate (Holm-Nielsen et al., 2009), which is a co-product of biogas. The digestate has a higher nutrient availability and homogeneity and a better C/N ratio than the animal manure. Another advantage is odour neutrality, and also ammonia odours disappear shortly after application (Al Seadi, 2008). The digestate is a solid-liquid suspension with macronutrients such as Nitrogen, phosphor, potassium, calcium, sulphur, magnesium, and micronutrients such as chloride, manganese, iron, zinc, copper, and nickel. The nutrients can be concentrated by a separation of the solid and liquid phases with higher nitrogen content in the liquid phase and higher phosphorus content in the solid phase (Logan and Visvanathan, 2019). The production of fertilisers from biomethanation is thus an essential factor in the production and not just the generation of energy (Ahluwalia and Patel, 2018).

The presence of toxic substances in the fertiliser, such as heavy metals, inorganic as well as persistent organic substances influences its quality and commercialisation. Notwithstanding the many benefits, the presence of contamination with toxic substances can result in negative public awareness regarding the anaerobic digestion technology and can bring about aesthetic damage to the environment. To prevent a negative impact on humans and the environment, a post-treatment of the digestate can be done. With quality controls and requirements, a standard for digestate can be produced (Logan and Visvanathan, 2019). A mixture of organic waste to the digestion of animal manure has been known to bring about significant advantages such as enhanced biogas production, an improved fertiliser value for the digestate, reduced greenhouse gas emissions, and savings corresponding to organic waste treatment (Hjorth et al., 2009). Due to the attenuated energy balance and decreased emissions of aldehydes, ammonia, esters, and other volatile compounds, anaerobic digestion is considered to be superior to other methods such as composting and incineration and is used to recover nutrients and energy from biodegradable matter (De Bere, 2000; Edelmann et al., 1999).

Biogas substrates can include all biomass types since they contain carbohydrates, hemicellulose, cellulose, and fats as the main constituents (Weiland, 2010). One of the excellent substrates for biogas production is Vegetable waste due to its high carbohydrate and moisture content (Patil and Deshmukh, 2015). Different types of feedstocks require different processes. That is why nowadays, ‘co-digestion’ is used in most biogas plants, i.e., two or more different feedstock types can be mixed in one digester. For example, the following types of waste are commonly used for digestion: animal manure and slurry, agricultural waste, crop leftovers, biowaste from households, market waste, wastewater sludge, and biodegradable waste from the industry as well (Al Seadi, 2008). Focused on biowaste, the fraction which can be used for anaerobic digestion is an organic portion of household waste, fruit and vegetable market wastes, restaurant food wastes, animal manure, and crop residues. The composition of biodegradable waste depends on India's area and season and is influenced by environmental conditions, as well as lifestyles, practices, and habits (Breitenmoser et al., 2018). Not all materials are equally well suited for anaerobic digestion, for example, garden residues are harder to decompose because of their long-chain hydrocarbons than food waste, due to which they require a longer retention time in the digester (Logan and Visvanathan, 2019). The most popular feedstock for biomethanation is animal waste, especially in rural areas. Animal manure, along with various micro-organisms, has a moisture content of about 75–92% and volatile solids of about 72–93% with a good buffering capacity (Fujino et al., 2005; Müller et al., 2004). With the world's largest livestock population, the availability is very high and can easily be used in family-scale plants. Therefore, it would be better to concentrate on biowaste digestion to get waste management under control (Rupnar et al., 2018).

However, animal manure can be utilised directly as fertiliser without further treatment. Besides, reports have shown that cow manure is an excellent substrate of biogas and it has the potential to generate 72 million cubic metres of biogas, which will be capable of meeting the cooking requirements of additional 100,000 households in India which could be further increased by using food and municipal waste (Misal and Deshmukh, 2020).

The methane yield depends on the composition of biowaste and is restricted by the substrate's carbon level. Theoretically, the maximum yield rate can be predicted from chemical analysis, but practical limitations exist because of complex carbon compounds that are not accessible in microbial digestion, and also, a part of carbon is required for micro-organism growth (Breitenmoser et al., 2018). ULBs delegated by the state government have a long list of functions, e.g., landfill or collection. The ULB operates about 645 small-capacity biogas plants. Ministry of New and Renewable Energy (MNRE) documented 4.3 million family-type biogas plants at the household, community, and organisation levels (Sharma and Jain, 2019). These family-type digesters have many advantages, e.g., simple, and cheap manufacture, robust construction, and smooth operation. There is no need for control instruments and process heating because of the warm climate and the long hydraulic retention time (HRT) (Al Seadi, 2008). In Indian cities like Pune, Bengaluru, Mumbai, Delhi, Coimbatore, Matheran, Vadodara, and Nasik, small-scale biomethanation plants are working efficiently and generate electricity. Altogether, these decentralised plants only use about 10% of the city's biodegradable waste. However, some plants are non-operating. E.g., in Bengaluru, 15 biomethanation plants are hardly in operation because of inadequate segregation of waste (Ahluwalia and Patel, 2018).

Another NGO, the Rajasthan Gow Seva Sangh (RGSS), makes a significant contribution to the sustainability of industries by introducing rules such as 'creating value from waste'. One of their activities was to support a dairy by using cow's milk and urine. Products such as pesticides, fertilisers, and traditional medicines were derived from the urine and marketed, and the manure was used to produce biogas as well as for fertilisers. By marketing and reusing all by-products, they created a production cycle, and by using local resources, they helped the farmers in the area (Surie, 2017). A company also demonstrated the profitability of biogas from livestock farming near Bangalore. A biogas plant on a poultry and dairy farm was put into operation in 2011, creating a production cycle as described in the case above. The biogas plant uses cow dung and poultry waste as a resource, the sludge is used or sold on the farm, and energy is produced from the biogas. Twenty-five percent of the energy produced was consumed on the premises, and 75 % was offered for sale (Surie, 2017).

Furthermore, it has been reported that MSWM by employing composting, anaerobic digestion, and landfill together were found to be preferable options to decrease GHG emissions in Mumbai. In Maharashtra, the AD of municipal biowaste, manure/crop residues comprise about 50–60% and 10% of total energy for cooking in villages and cities respectively (Gross et al., 2021). A novel initiative 'Swachh Bharat (clean India) Mission' provides better opportunities for anaerobic digestion and waste management. (Breitenmoser et al., 2019).

These cases described above clearly show that bio-methanation is applicable but on a small scale. Because of the uncooperative collaboration of concessioners and consignees, larger biogas plants are not yet successful in India (Sharma and Jain, 2019). The improper separation of organic and non-organic waste, dust, and inert material that exists in the feedstock is one more reason for the same. In this case, sorting of the waste from other materials is essential before leading into the plant. Appropriate technologies for the separation of waste are not yet available or are not introduced for financial reasons. Another reason for the decommissioning of waste to energy plants is the non-delivery of promised amounts of waste. Poor collection and unorganised transport of waste interrupt the supply chain and influence the process. All together leads to the slow growth of waste in India's energy sector (Mittal et al., 2018).

4 Discussion

4.1 Barriers of biogas plants

As a renewable energy source, biogas is a significant constituent as a measure to combat environmental issues such as increased greenhouse gas emissions, deforestation, increased energy consumption, and inefficacious management of waste (Nevzorova and Kutcherov, 2019). The potential of biogas from municipal wastes is dependent on the organic fraction, which can be employed for the generation of biogas through anaerobic digestion (Abbasi et al., 2011; Rios and Kaltschmitt, 2016). Various barriers obstruct the uptake of biogas technology as a source of energy, and it is necessary to understand them. There have been many studies that focus on the barriers of biogas plants as a whole and in particular regions.

In rural areas, there are many households with low-income, and it is difficult for them to set up even a small-scale biogas plant. The cost of building and installing a family-type digester with a capacity of 1 m^3 of Biogas per day is \$348 on average. Depending on the capacity, the government provides financial support of around \$ 123–200 for family-scale biogas plants. With an income of \$150, the purchase and installation cost far exceed the monthly budget. Further, it is difficult to get a loan for the installation of a biogas plant. The central government initiated a program called NBMMP, which provides a subsidy for installing a biogas plant. Therefore, one of the criteria is ownership of 2-3 cattle, which many low-income households do not have. That is why it is burdensome for them to get a loan of money, thereby hindering the dissemination of biogas technologies (Mittal et al., 2018).

One of the factors that obstruct the establishment of biogas plants in rural areas is the social-cultural barrier. Reluctancy of people to make use of night soil for the biogas plant due to social disgrace has been a significant issue (Mittal et al., 2018). For the efficacious operation or functioning of the biogas plants, sufficient water supply and substrate are the critical factors. Underfeeding of substrates or supply of substrates in wrong ratios can majorly affect the biogas plant's functioning leading to its failure, and this results in a negative perception among users in the rural areas. People in rural areas own a minimum of 2–3 cattle, which cannot provide the required quantity of substrates to the biogas plant. Moreover, under-collection of cow dung due to grasing and roaming of cattle in the fields can further lead to under-feeding of substrates, which disrupts the proper functioning of biogas plants (Mittal et al., 2018).

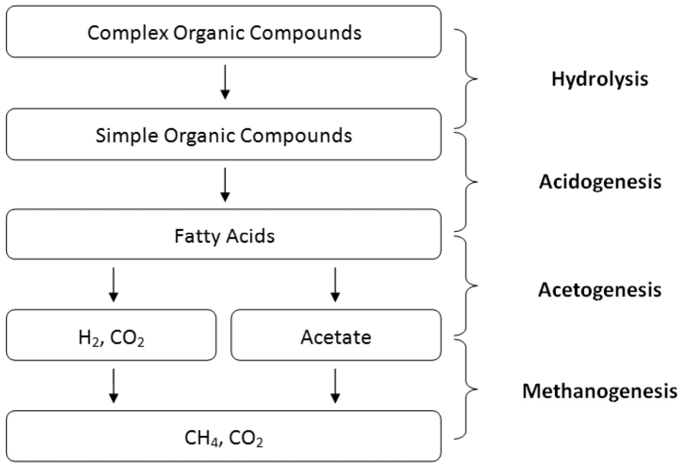
Although biogas has many advantages over conventional fuels, it competes with cheaper alternatives like firewood. For a simple reason, namely, a constant supply of fuel can be ensured with easy procurement. For example, in the Sirsi area, biogas has a high dissemination rate because liquid petroleum gas (LPG) has limited accessibility. Similarly, obtaining electricity from other renewable sources such as the sun, water, and wind is cheaper than anaerobic production (Fthenakis and Kim, 2010). This aspect is due to government support, and also the handling cost and waste transport over long distances are high, negatively influencing the power plant economics. This demerit affects the economic survival of biogas plants and hinders the overcome of coal power plants (Mittal et al., 2018).

4.2 The biochemical process of anaerobic digestion

As mentioned before, the biochemical process of anaerobic digestion results from the decomposition of organic matter in the absence of oxygen, generating biogas, and digestate. The whole process is subdivided into four prime process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 4). The chemical process of decomposition depends on specific micro-organisms in each sub-step. As a result, the material in each step can be further broken down. The maximum biogas yield is reached during methanogenesis, while in the process of hydrolysis, only a small amount of biogas is produced (Al Seadi, 2008).

The first step of AD is hydrolysis, a process in which the complex organic matter is degraded into smaller items, i.e., polymers like carbohydrates, lipids, nucleic acids, and proteins are converted into monomers like glucose, glycerol, purines, and pyridines (Al Seadi, 2008). The products resulting from hydrolysis are transformed during acidogenesis by acidogenic bacteria into methanogenic substrates. This conversion means that simple sugars, amino acids, and fatty acids are decomposed into acetate, carbon dioxide, and hydrogen (70%) as well as into volatile fatty acids (VFA) and alcohols (30%) (Al Seadi, 2008). Some acidogenesis products are not converted to methane directly and hence these products are converted into methanogenic substrates in the process of acetogenesis. VFA and alcohol oxidize into methanogenic substrates like acetate, hydrogen, and carbon dioxide. In this process step, it is essential to maintain a low partial hydrogen pressure because if the hydrogen content gets too high, the anaerobic metabolism will be disturbed (Bharathiraja et al., 2018). In the last process step, methanogenesis, methane, and carbon dioxide are produced from intermediates by methanogenic bacteria. There are two categories of methanogenic bacteria: acetotrophic and hydrogenotrophic bacteria. Acetotrophic bacteria convert acetate into methane and carbon dioxide, and the hydrogenotrophic methanogens generate methane out of hydrogen (Bharathiraja et al., 2018). The total methane yield is distributed with 70% on acetotrophic and 30% on hydrogenotrophic bacteria (Al Seadi, 2008).

Figure 4 Steps in the anaerobic digestion process



4.3 Operational factors involved in AD

Methanogenesis is influenced by several conditions such as temperature, pH, and composition of the feedstock. Further, it is the slowest biochemical reaction of the entire process and can affect methane yield (Al Seadi, 2008). As a result, the process must be matched to the feedstock, and all other influences must be taken into account because methanogenic bacteria are sensitive to the environment as they only work in strictly anaerobic conditions (Rupnar et al., 2018). The parameters which affect the efficiency of anaerobic digestion are temperature, pH value, C/N ratio, nutrient supply, retention time, stirring intensity, and the exclusion of oxygen (Al Seadi, 2008) and thus optimising and maintaining the process of anaerobic digestion is the key to enhance the biogas yield (Ghosh et al., 2020). The following paragraphs will focus on a few critical influencing parameters.

Anaerobic digestion can take place in three different temperature ranges: psychrophilic (below 25°C), mesophilic (25–45°C), and thermophilic (45–70°C). The temperature influences the retention time, which is the duration needed for the bio-methanation. The retention time can be shortened with a higher temperature. However, this must be adapted to the respective material to achieve an optimum methane yield. Therefore, the choice of the applied temperature is a decisive factor in the process development and must be decided based on the feedstock. Most biogas plants operate at thermophilic process temperatures because of many benefits compared to mesophilic and psychrophilic processes (Al Seadi, 2008). Due to the higher temperature, the killing of pathogens in the substrate is more likely at thermophilic temperatures, the growth of microbes is higher, and the hydraulic retention time is lower. Likewise, with a higher temperature, productivity can be increased. The anaerobic digestion in the thermophilic area requires high energy and causes process instability, which may negatively affect energy balance and the whole digestion process, respectively (Panigrahi and Dubey, 2019). Thermophilic bacteria are susceptible to temperature fluctuations. With a deviation of ±1°C, it may already adversely affect methane production. Therefore, a constant temperature during the entire process is essential. Mesophilic bacteria have the advantage that they can compensate for temperature fluctuations up to ±3°C (Al Seadi, 2008).

Another critical parameter is the pH value, as it influences the growth of methanogenic micro-organisms. Production of large quantities of organic acids in the initial digestion period occurs, thereby decreasing the pH of the mixture. During digestion, nitrogen is digested, and hence the ammonia concentration is increased, which in turn increases the pH of the mixture. A pH of 7.2–8.2 is attained when methane production is stabilised (Shefali and Themelis, 2002).

For mesophilic digestion, the optimum pH value is in the range of 6.5–8.0. For thermophilic digestion, the pH value is usually higher. To compensate for fluctuations in the pH value, a buffer system, usually bicarbonate, is used. The buffer can balance the pH well to a certain level, depending on alkaline and acidic components in the liquid phase (Al Seadi, 2008). There is also the opportunity to separate the process into two-stage reactors. This additional step will increase the cost of installing and operating (Panigrahi and Dubey, 2019).

The main component of biogenic waste is carbon, the energy source for anaerobic micro-organisms and therefore essential for anaerobic digestion. C/N ratio is the term expressed for the relative proportions of carbon and nitrogen present in the organic matter or the biogenic waste. Micro-organisms require a specific C/N ratio for metabolism. For an optimal process, the C/N ratio should be in the range of 20 : 1 to 30 : 1, with 25 : 1 being the most optimal ratio. The C/N ratio of the organic fraction in MSW is generally high because of carbonaceous material such as paper, and garden waste, and thereby well suited for the anaerobic digestion (Panigrahi and Dubey, 2019).

If the C/N ratio is exceptionally high, the methanogens consume nitrogen expeditiously in order to meet their protein requirements, and hence it is no more available to react with the remaining carbon present in the organic matter, thus reducing the production of biogas (Porras and Gebresenbet, 2003). In contrast to it, if the C/N ratio is inadequate, nitrogen release occurs, which assembles in ammonia formation, resulting in an increase in the pH of the organic matter. Consequently, toxic effects are exerted on the methanogenic bacteria due to the rise in a higher pH(>8.5) (Abbasi and Abbasi, 2012; Hartmann and Ahring, 2006).

The duration for which the organic substrate and the micro-organism should abide together in order to attain a desired level of degradation is called the ‘retention time’ (Porras and Gebresenbet, 2003). In the process of anaerobic digestion, we must differentiate two retention times: the solid retention time (SRT), which is defined as the average time for which the biomass is retained in the system, and the hydraulic retention time, which is defined as the average time for which the substrate (either in solid or liquid form) is retained. The SRT should always be greater than the HRT to take full use of the adaptability of bacteria for the biodegradation process. It is vital to ensure that the SRT is sufficient for the complete development of organisms. However, if the SRT is too long, then it can also lead to the fact that the individual sub-processes can no longer be separated from one another and thus adversely affect the anaerobic digestion (Chatterjee and Mazumder, 2019).

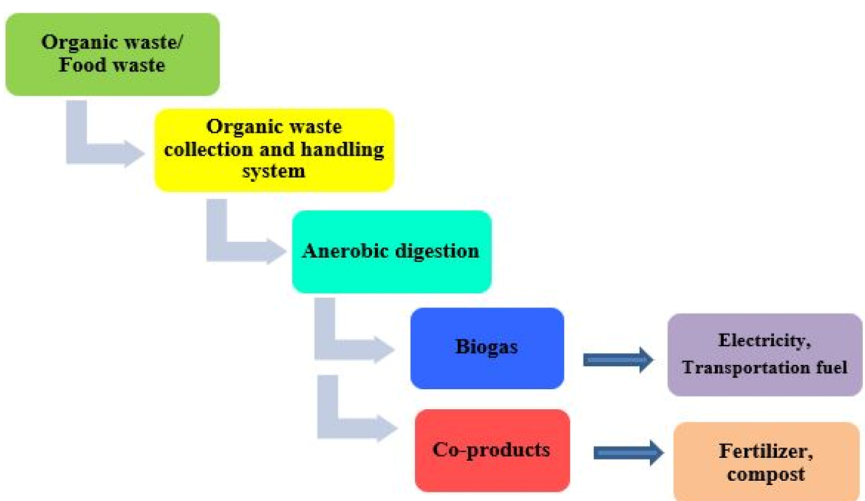
Ammonia (NH_3) is an essential nutrient for fertilisers, but increased ammonia concentration (due to the high proportion of protein) can impede the fermentation process. Particularly in the case of animal waste, the risk of inhibition is significant for high concentrations of ammonia are present in the urine. An optimal ratio between the nutrients is essential to prevent inhibition or disruption of the process. This ratio not only applies to ammonium but also to carbon, nitrogen, phosphorus, sulphur, and many other microelements (Al Seadi, 2008).

4.4 Biogas components and consequences

Biogas is a versatile energy supplier, appropriate for many applications. The simplest one is the direct use for cooking and lighting, which is already operated in 4.3 million family-type biogas plants in India. Many countries use biogas for combined heat and power applications, as fuel for vehicles, or in fuel cells (Al Seadi, 2008). Biogas can be produced and consumed without degrading the environment and, therefore, is a sustainable, renewable, and environmentally friendly energy source (Rupnar et al., 2018; Wresta and Saepudin, 2018).

The main components of biogas are methane (CH_4, 50–75%), carbon dioxide (CO_2, 25–50%), and other gases (2–8%), such as nitrogen, oxygen, and traces of hydrogen sulphide (H_2S), ammonia (NH_3) and hydrogen (H_2) (Breitenmoser et al., 2018). The presence of these impurities depends on the source of Biogas, i.e., manure fermentation (Kadam and Panwar, 2017). CH_4, an important substitute fuel, generates both heat and electricity and replaces the vehicle fuel (Dhar et al., 2017). Biogas generated from waste can be directly used to generate power and electricity for vehicular use and domestic cooking (Figure 5). Before using the biogas for engine application, hydrogen sulphide and water vapour must be removed because H_2S combustion generates sulphur dioxide (SO_2), which reacts with water vapour to form sulphurous acid (H_3SO_3) (Kulkarni and Ghanegaonkar, 2019), thus corroding vital mechanical components which can lead to engine failure and can also cause maintenance issues. For a higher power output and efficiency, methane is enriched by the removal of carbon dioxide. The process of methane enrichment and the removal of impurities also make storage and transportation easier. Through various techniques, methane enrichment can be achieved up to 90% (Rupnar et al., 2018).

Figure 5 Framework for the use of AD (see online version for colours)



An additional advantage of the removal of CO_2 is that biogas can be compressed in cylinders, making it available as automobile fuel and also biomethane, which can be used for CNG applications (Kapdi et al., 2005; Persson et al., 2006). In addition to the benefits of biogas high auto-ignition resistance and a requirement of less air for its combustion, it endures negative features due to slow flame velocity, low energy density, and incomplete combustion (Crookes, 2006; Roubaud et al., 2002).

Installation of biogas can improve the health of users since it reduces the pathogenic content of the substrate materials by anaerobic digestion of animal and human wastes thus providing sanitation, particularly in places where public toilets are linked to the biogas plants (Bond and Templeton, 2011).

With the advancement of technology, there are nowadays many different possibilities to produce electricity for households and industries from Biogas (Figure 6). The first step consists of converting the chemical energy of methane into mechanical energy in a controlled combustion system. A subsequent generator converts this mechanical energy into electrical energy. Depending on the methane content, about 1.5 kW of electricity can be generated from 1 m^3 of biogas (Rupnar et al., 2018). As already mentioned, biomass is the most important energy source for many households in rural areas. 87% of households in rural areas and 26% of urban households use biomass for cooking. Biogas has a higher heating value than natural gas and coal and is therefore very economical to use. A 25 kg of fresh manure can yield 5 kg of dry manure, of which 1 m^3 biogas can be produced. Further, biogas burns with a clean blue colour flame, i.e., the room stays clean, and the people are not exposed to any health risks (Rupnar et al., 2018). Due to biogas's potential in its diverse applications, there emerges a commercial need to make it transportable, and hence Biogas storage by scrubbing and compression and higher pressures is necessary (Kapdi et al., 2005).

Figure 6 Various approaches to combat MSWM related problems (see online version for colours)

4.5 Industrial Disruptive technologies as a source of waste reduction

The biological, labour, and personality entities of humans are sequentially correlated with the economic formations created by industrial revolutions. Particularly, the third industrial revolution that was initiated by the EU countries mainly focused on a green economy and as an approach to resolving global environmental issues. Besides, the purpose of the green economy is directed towards dematerialisation and reduced energy intensity of socio-economic systems through alternative energy, additive technologies, and horizontal production/consumption systems, with the key interests being green energy development, utilisation of infrastructure facilities for renewable energy installations, the establishment of efficient energy-saving systems, designing of the information and energy system (EnerNet) to regulate the energy production processes and distribution, and the electrification of transport (Melnyk et al., 2019).

5 Conclusions

Energy is an integral part of socio-environmental development and economic growth. Biogas technology has the potential for sustainable development, especially in India, due to the high organic content in the solid waste. It can play a crucial role in reducing GHG emissions and protecting forests. The use of fertiliser out of the slurry improves soil health and thus increases agricultural production. With the use of bio-fertiliser in agriculture, the production of chemical fertilisers could be reduced, and much energy required to produce chemical fertilisers could be saved. Anaerobic digestion is an important WTE technology to help India face its problem with MSW. This method has benefits for humans as well as for the environment.AD can be used to produce methane, which is used as a versatile source of energy. It leads to a sustainable disposal methodology with the simultaneous reduction of MSW.

Biogas technology is not the main problem in India, but the storing of MSW in the right place. Before any further actions for bio-methanation are taken, a logistic system for MSW must be set up by the government. All scientific papers dealing with MSWM in India come to the same cause for the problem, namely a lack of understanding of the inhabitants for an environmental disposal, a non-functioning collection, and transportation. Purely technical considerations will not bring a solution in the longterm. Effective waste management requires development strategies for collection, segregation, and transportation. Residents need to be enlightened about the gravity of the situation and the effects of improper waste disposal on the environment. Accordingly, incentives must be created to change people's behaviour. The public should realise that one such approach to resolving the issues related to SWM lies in the usage of waste as a 'resource' rather than being destroyed.

There is a need to divert an organic fraction of MSW from going into landfills to recycling. The perception of waste must change, from the consideration of waste as a resource to marketing as a product. A change in people's manners must be achieved first to change this perception. Therefore, many waste disposal options are missing. The human tendency is to go in the path of least resistance. It is easier to throw the waste to already existing dumping to search for waste containers, and of these, there are clearly few. The first step would be to provide waste containers in every street, especially in big cities, with a separation into wet waste or other organic waste, recyclables, and non-recyclables, as they already exist in airports and railway stations. The potential of MSW utilisation must be exhausted to accomplish a circular economy. Only with the solution to this waste management problem India can go further and launch big-scale biogas plants to guarantee a constant feedstock. Instead of disposing of the untreated solid waste in landfills, organic waste can be treated and provide India with energy, and the amount of disposal will decrease, including greenhouse gases and leachate.

Conflicts of interest

The author declares no conflict of interest.

References

Abbasi, T. and Abbasi, S.A. (2012) 'Is the use of renewable energy sources an answer to the problems of global warming and pollution?', *Critical Reviews in Environmental Science and Technology*, Vol. 42, No. 2, pp.99–154.

Abbasi, T., Tauseef, S.M. and Abbasi, S.A. (2011) *Biogas Energy*, Vol. 2, Springer Science & Business Media, Pondicherry.

Ahluwalia, I.J. and Patel, U. (2018) *Solid Waste Management in India: An Assessment of Resource Recovery and Environmental Impact*.

Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavendhan, S. and Iyyappan, J. (2018) 'Biogas production – a review on composition, fuel properties, feed stock and principles of anaerobic digestion', *Renewable and Sustainable Energy Reviews*, Vol. 90, April, pp.570–582.

Bharti, V., Singh, J. and Singh, A.P. (2017) 'A review on solid waste management methods and practices in India', *Trends in Biosciences*, Vol. 10, No. 21, pp.4065–4067.

Bond, T. and Templeton, M.R. (2011) 'History and future of domestic biogas plants in the developing world', *Energy for Sustainable Development*, Vol. 15, No. 4, pp.347–354.

Breitenmoser, L., Dhar, H., Gross, T., Bakre, M., Huesch, R., Hugi, C., Wintgens, T., Kumar, R. and Kumar, S. (2018) 'Methane potential from municipal biowaste: insights from six communities in Maharashtra, India', *Bioresource Technology*, Vol. 254, pp.224–230.

Breitenmoser, L., Gross, T., Huesch, R., Rau, J., Dhar, H., Kumar, S. and Wintgens, T. (2019) 'Anaerobic digestion of biowastes in India: opportunities, challenges and research needs', *Journal of Environmental Management*, Vol. 236, pp.396–412.

Chatterjee, B. and Mazumder, D. (2019) 'Role of stage-separation in the ubiquitous development of anaerobic digestion of organic fraction of municipal solid waste: a critical review', *Renewable and Sustainable Energy Reviews*, Vol. 104, pp.439–469.

Crookes, R.J. (2006) 'Comparative bio-fuel performance in internal combustion engines', *Biomass and Bioenergy*, Vol. 30, No. 5, pp.461–468.

de Araújo, A.S.F., de Melo, W.J. and Singh, R.P. (2010) 'Municipal solid waste compost amendment in agricultural soil: changes in soil microbial biomass', *Reviews in Environmental Science and Bio/Technology*, Vol. 9, No. 1, pp.41–49.

De Bere, L. (2000) 'Anaerobic digestion of solid waste: state-of-the-art', *Water Science and Technology*, Vol. 41, No. 3, pp.283–290.

Dhar, H., Kumar, S. and Kumar, R. (2017) 'A review on organic waste to energy systems in India', *Bioresource Technology*, Vol. 245, pp.1229–1237.

Edelmann, W., Joss, A. and Engeli, H. (1999) 'Two step anaerobic digestion of organic solid wastes', *II Int. Symp. Anaerobic Dig. Solid Waste*, June, pp.15–17.

Energy, R. and Forward, F.C.A.W. (2010) *Ministry of New and Renewable Energy*, GOI, New Delhi.

Fthenakis, V. and Kim, H.C. (2010) 'Life-cycle uses of water in US electricity generation', *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 7, pp.2039–2048.

Fujino, J., Morita, A., Matsuoka, Y. and Sawayama, S. (2005) 'Vision for utilization of livestock residue as bioenergy resource in Japan', *Biomass and Bioenergy*, Vol. 29, No. 5, pp.367–374.

Ghosh, A., Das, B. and Sarkar, J.P. (2017) *Biomethanation Technology of Municipal Solid Waste Practices in India: An Approach Towards Waste to Energy*, Haldia.

Ghosh, P., Shah, G., Sahota, S., Singh, L. and Vijay, V.K. (2020) 'Biogas production from waste: technical overview, progress, and challenges', *Bioreactors*, Vol. 7, pp.89–104.

Ghosh, S.K. (2018) 'Waste management and resource efficiency', *Proceedings of the 6th IconSWM 2016*, Kolkata.

Gross, T., Breitenmoser, L., Kumar, S., Ehrensperger, A., Wintgens, T. and Hugi, C. (2021) 'Anaerobic digestion of biowaste in Indian municipalities: effects on energy, fertilizers, water and the local environment', *Resources, Conservation and Recycling*, Vol. 170, p.105569.

Hartmann, H. and Ahring, B.K. (2006) 'Strategies for the anaerobic digestion of the organic fraction of municipal solid waste: an overview', *Water Science and Technology*, Vol. 53, No. 8, pp.7–22.

Hjorth, M., Nielsen, A.M., Nyord, T., Hansen, M.N., Nissen, P. and Sommer, S.G. (2009) 'Nutrient value, odour emission and energy production of manure as influenced by anaerobic digestion and separation', *Agronomy for Sustainable Development*, Vol. 29, No. 2, pp.329–338.

Holm-Nielsen, J.B., Al Seadi, T. and Oleskowicz-Popiel, P. (2009) 'The future of anaerobic digestion and biogas utilization', *Bioresour. Technol*, Vol. 100, pp.5478–5484.

Joshi, R. and Ahmed, S. (2016) 'Status and challenges of municipal solid waste management in India: a review', *Cogent Environmental Science*, Vol. 2, No. 1, p.1139434.

Kadam, R. and Panwar, N.L. (2017) 'Recent advancement in biogas enrichment and its applications', *Renewable and Sustainable Energy Reviews*, Vol. 73, pp.892–903.

Kapdi, S.S., Vijay, V.K., Rajesh, S.K. and Prasad, R. (2005) 'Biogas scrubbing, compression and storage: perspective and prospectus in Indian context', *Renewable Energy*, Vol. 30, No. 8, pp.1195–1202.

Kleerebezem, R., Joosse, B., Rozendal, R. and Van Loosdrecht, M.C. (2015) 'Anaerobic digestion without biogas?', *Reviews in Environmental Science and Bio/Technology*, Vol. 14, No. 4, pp.787–801.

Kougias, P.G. and Angelidaki, I. (2018) 'Biogas and its opportunities – a review', *Frontiers of Environmental Science & Engineering*, Vol. 12, No. 3, p.14.

Kulkarni, M.B. and Ghanegaonkar, P.M. (2019) 'Methane enrichment of biogas produced from floral waste: a potential energy source for rural India', *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, Vol. 41, No. 22, pp.2757–2768.

Kumar, S. (2011) 'Composting of municipal solid waste', *Critical Reviews in Biotechnology*, Vol. 31, No. 2, pp.112–136.

Kumar, S., Malav, L.C., Malav, M.K. and Khan, S.A. (2015) 'Biogas slurry: source of nutrients for eco-friendly agriculture', *International Journal of Extensive Research*, Vol. 2, No. 2, pp.42–46.

Kumar, S., Smith, S.R., Fowler, G., Velis, C., Kumar, S.J., Arya, S. and Cheeseman, C. (2017) 'Challenges and opportunities associated with waste management in India', *Royal Society Open Science*, Vol. 4, No. 3, p.160764.

Logan, M. and Visvanathan, C. (2019) 'Management strategies for anaerobic digestate of organic fraction of municipal solid waste: current status and future prospects', *Waste Management & Research*, Vol. 37, 1_suppl, pp.27–39.

Mani, S. and Singh, S. (2016) 'Sustainable municipal solid waste management in India: a policy agenda', *Procedia Environmental Sciences*, Vol. 35, pp.150–157.

Melnyk, L.H., Kubatko, O.V., Dehtyarova, I.B., Dehtiarova, I.B., Matsenko, O.M. and Rozhko, O.D. (2019) 'The effect of industrial revolutions on the transformation of social and economic systems', *Problems and Perspectives in Management*, Vol. 17, No. 4.

Misal, V. and Deshmukh, S. (2020) 'Energy recovery from organic fraction of municipal solid waste and food waste by anaerobic digestion', *Energy*, Vol. 10, No. 1, p.54.

Mittal, S., Ahlgren, E.O. and Shukla, P.R. (2018) 'Barriers to biogas dissemination in India: a review', *Energy Policy*, Vol. 112, pp.361–370.

Mmereki, D. (2018) 'Current status of waste management in Botswana: a mini-review', *Waste Management & Research*, Vol. 36, No. 7, pp.555–576.

Müller, J.A., Winter, A. and Struenkmann, G. (2004) 'Investigation and assessment of sludge pre-treatment processes', *Water Science and Technology*, Vol. 49, No. 10, pp.97–104.

Nevzorova, T. and Kutcherov, V. (2019) 'Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review', *Energy Strategy Reviews*, Vol. 26, p.100414.

Panigrahi, S. and Dubey, B.K. (2019) 'A critical review on operating parameters and strategies to improve the biogas yield from anaerobic digestion of organic fraction of municipal solid waste', *Renewable Energy*, Vol. 143, pp.779–797.

Patil, V.S. and Deshmukh, H.V. (2015) 'Anaerobic digestion of vegetable waste for biogas generation: a review', *International Research Journal of Environment Sciences*, Vol. 4, No. 6, pp.80–83.

Persson, M., Jönsson, O. and Wellinger, A. (2006) 'Biogas upgrading to vehicle fuel standards and grid injection', *IEA Bioenergy Task*, Vol. 37, December, pp.1–34.

Porras, J.P. and Gebresenbet, G. (2003) *Review of Biogas Development in Developing Countries with Special Emphasis in India*, Sweden.

Pujara, Y., Pathak, P., Sharma, A. and Govani, J. (2019) 'Review on Indian municipal solid waste management practices for reduction of environmental impacts to achieve sustainable development goals', *Journal of Environmental Management*, Vol. 248, p.109238.

Raje, D.V., Wakhare, P.D., Deshpande, A.W. and Bhide, A.D. (2001) 'An approach to assess level of satisfaction of the residents in relation to SWM system', *Waste Management & Research*, Vol. 19, No. 1, pp.12–19.

Ramachandra, T.V., Bharath, H.A., Kulkarni, G. and Han, S.S. (2018) 'Municipal solid waste: generation, composition and GHG emissions in Bangalore, India', *Renewable and Sustainable Energy Reviews*, Vol. 82, pp.1122–1136.

Rao, A.V.K. and Maddaiah, G.P. (2010) 'Forage productivity of Para grass on reclaimed wastelands', *Int. J. Appl. Agric. Res.*, Vol. 5, No. 2, pp.195–204.

Rios, M. and Kaltschmitt, M. (2016) 'Electricity generation potential from biogas produced from organic waste in Mexico', *Renewable and Sustainable Energy Reviews*, Vol. 54, pp.384–395.

Roubaud, A., Röthlisberger, R. and Favrat, D. (2002) 'Lean-burn cogeneration biogas engine with unscavenged combustion prechamber: comparison with natural gas', *International Journal of Thermodynamics*, Vol. 5, No. 4, pp.169–175.

Rupnar, A.K., Jain, S. and Panwar, N.L. (2018) 'Biogas in India: potential and integration into present energy systems', *International Journal of Current Microbiology and Applied Sciences*, Vol. 7, No. 07, pp.2175–2186.

Al Seadi, T. (2008) *Biogas Handbook*, Vol. 1, University of Southern Denmark, Esbjerg.

Sharma, K.D. and Jain, S. (2019) 'Overview of municipal solid waste generation, composition, and management in India', *Journal of Environmental Engineering*, Vol. 145, No. 3, p.04018143.

Shefali, V. and Themelis, N.J. (2002) *Anaerobic Digestion of Biodegradable Organics in Municipal Solid Waste*, Department of Earth and Environmental Engineering in Columbia University, New York.

Shekdar, A.V. (2009) 'Sustainable solid waste management: an integrated approach for Asian countries', *Waste Management*, Vol. 29, No. 4, pp.1438–1448.

Surie, G. (2017) 'Achieving sustainability: insights from biogas ecosystems in India', *Agriculture*, Vol. 7, No. 2, p.15.

Swain, P.K., Biswal, T. and Panda, R.B. (2020) 'A short review on solid waste generations, recycling and management in the present scenario of India', *Journal of Industrial Pollution Control*, Vol. 34, No. 1, pp.2008–2014.

Weiland, P. (2010) 'Biogas production: current state and perspectives', *Applied Microbiology and Biotechnology*, Vol. 85, No. 4, pp.849–860.

Wresta, A. and Saepudin, A. (2018) 'Analysis of product and temperature of biogas combustion in various air biogas equivalence ratio and methane content', *Indonesian Journal of Chemistry*, Vol. 18, No. 2, pp.211–221.

Abbreviations

AD	Anaerobic digestion
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
CPCB	Central Pollution Control Board
GHG	Greenhouse gases
H_2	Hydrogen
H_2S	Hydrogen sulphide
HRT	Hydraulic retention time
LPG	Liquid petroleum gas
MNRE	Ministry of New and Renewable Energy
MT	Metric ton
MUD	Ministry of Urban Development
N	Nitrogen
NGO	Non-government organisation
NH_3	Ammonia
pH	Potential of hydrogen
RGSS	Rajasthan Gow Seva Sangh
SRT	Solid retention time
ULB	Urban Local Bodies
VFA	Volatile fatty acids
WTE	Waste-to-Energy