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# Recent Advances in Bio-Energy Research

## Select Proceedings of the 3rd International Conference, ICRABR 2022

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# Preface

Energy security and the Environment are the primary and important issues to any country. The exhaustive use of fossil fuel sources has raised a serious concern not only about energy security but also the negative impact on the environment. Now there is a shift in the current energy spectrum to green energy by creating and utilizing renewable energy sources. In line with the commitment to build a sustainable future for all, India has been pioneering the development of various clean and renewable sources of energy with the ultimate objective of ensuring universal access to affordable, reliable, and modern energy services. As a result of this unwavering commitment, the country is having the 4th largest renewable energy capacity in the world.

Agricultural biomass is an abundant renewable resource, which can be converted into biofuels forming a sustainable alternative to substitute fossil fuels. This also is attracting various stakeholders for advancing Research & Development in focusing on new-age solutions to advance the Energy Transition. Biomass meets a major fraction of energy demand in rural areas in developing countries like India. Biomass, which includes agricultural waste, firewood, animal dung, etc., accounts for the major primary energy used in India. With the huge availability of biomass, there is a huge potential for power generation. Keeping in view the amalgamation of these issues and potential, the proceeding of 3rd International Conference on Recent Advances in Bio-Energy Research (ICRABR2022) is being presented herewith. The conference covered the following themes:

- Biofuels and Biogas
- Biomass Hybrid Systems
- Electrochemical Conversion of Biofuels to Renewable Energy
- Nanotechnology for Biofuels and Bio-energy
- Waste Management
- Bio-energy Policy and Strategies.

The conference was organized virtually during 9–11, March 2022, with a hybrid inauguration on March 9, 2022. The conference received more than 80 abstracts/papers from various researchers, students, and academicians and witnessed 6 plenary and 10 keynote speakers from Europe, North America, and Asia in the three-day program. Conference sessions and speakers highlighted the research activities in the areas of bio-energy including biodiesel, bioethanol, biomethanation, fuel cell, biomass-derived electrodes for energy generation, biomass gasification, and biomass cookstove. The conference brought together members of the scientific community, industry, entrepreneurs, students, and organizations who gathered to discuss strategies, recent advances, and policies in the field of bio-energy.

Overall response to the conference was quite encouraging. A large number of papers were reviewed and after a rigorous review process, only 22 papers were selected for inclusion in the conference proceeding. Further, the proceeding is categorized into five sections. We are confident that the papers presented in this proceeding shall provide a platform for young as well as experienced professionals to generate new ideas and research in the field of bioenergy.

The editorial team members would like to extend their gratitude and sincere thanks to all contributed authors, reviewers, panellists, plenary and keynote speakers, and the organizing team of the conference for paying attention to the quality of the proceeding. We are also thankful to our sponsors for supporting the event. We also extend our sincere thanks to Springer for agreeing to be our publishing partner for this proceeding.

New Delhi, India — Nikhil Gakkhar
Kapurthala, India — Sachin Kumar
Kapurthala, India — Anil K. Sarma
Richland, USA — Neal T. Graham
September, 2023

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# About the Editors

**Dr. Nikhil Gakkhar** is Scientist C in the Ministry of New and Renewable Energy, Government of India and is handling Solar Water Pumping program throughout India. Prior to that, he worked at Sardar Swaran Singh National Institute of Bio-Energy, Kapurthala India and acted as Visiting Faculty for the Masters in Technology program in Renewable Energy at the Dr. BR Ambedkar National Institute of Technology, Jalandhar, India. He was the Project Coordinator for the South Asia Group on Energy (SAGE) US-India energy cooperation and worked closely with Lawrence Berkeley National Laboratory and the Pacific Northwest National Laboratory, USA. He has a keen research interest and expertise in renewable energy like solar thermal, concentrators, hybrid systems, biomass thermochemical conversion, etc. Presently, he has more than 30 international research articles published in SCI journals of high repute, including conferences and book chapters. He has also filed an Indian patent on the innovative solar-concentrating cooling system.

**Dr. Sachin Kumar** is a Deputy Director in the Biochemical Conversion Division at the Sardar Swaran Singh National Institute of Bio-Energy, Kapurthala, India. He was a Visiting Professor in the Department of Chemical and Biological Engineering at the South Dakota School of Mines and Technology, Rapid City, USA, for a year. He obtained his Ph.D. degree in Chemical Engineering from the Indian Institute of Technology (IIT) Roorkee, India, and has research experience in the biochemical conversion of biomass to biofuels, including bioethanol, biogas, biohydrogen, lignin valorization, etc. He has completed eight research projects and one consulting project. Dr. Kumar has published more than 75 papers in peer-reviewed journals, book chapters, papers in conference proceedings, and ten edited books. He has one granted US patent and five filed Indian patents. He has delivered more than 80 invited or plenary lectures and presented more than 75 papers at national and international conferences. He is a recipient of 2016 ASM-IUSSTF Indo-US Research Professorship and selected as Bioenergy-Awards for Cutting Edge Research (B-ACER) Fellow 2016 by DBT and IUSSTF. He has also secured the place among the top 2% researchers in the world based on Scopus reported by Stanford University, USA.

**Dr. Anil Kumar Sarma** is an M.Sc. Chemistry (1997), M.Tech. in Energy Technology (2002) and Ph.D. in Energy (2006) with specialization in Bioenergy. He also worked as research associate at IIT Guwahati (2007–08) and visiting researcher at Seikei University, Japan (2008–09). He is currently working as Scientist-E at Sardar Swaran Singh National Institute of Bio-Energy, Kapurthala, India and has published more than 65 articles in Catalysis, Biofuel, Enzyme and applications; biomass derived catalyst, applications for biofuel synthesis and biomass for activated carbon production for different utilities. He has edited 4 books and 10 book chapters. He has guided over 20 Master's thesis, 6 Ph.D. thesis, and 8 postdoctoral fellows. He has completed several R&D projects on biofuel and catalysis and is currently working on research projects on biomass characterization for power plant applications as a substitute of coal. He is a recipient of outstanding research achievement awards (OIRA 2022) from Oxford Research Awards in the field of Biofuel, Catalysis, and Applications of Biofuels in IC Engine. He is also a visiting faculty at the Centre for Energy and Environment, Dr. BR Ambedkar National Institute of Technology, Jalandhar.

**Dr. Neal T. Graham** is an Earth Scientist at the Joint Global Change Research Institute at the Pacific Northwest National Laboratory. His research focuses on the interactions between human and water systems through the lens of multisector dynamics and integrated assessment. Additionally, he explores the near- and long-term implications of energy futures across the world and their associated drivers of change. His research interests include integrated assessment modelling, virtual water trade, near-term climate implications, and human-water interactions. Dr. Graham holds a B.S. in Meteorology from Rutgers University and an M.S. and Ph.D. in Atmospheric and Oceanic Sciences from the University of Maryland, USA.

# Part I
# Biochemical Conversion

# Chapter 1
# Analysis of Methane Emission Reduction of Biogas Plant at Bhopal

**Prakhar Badal and Savita Vyas**

**Abstract** The term climate change refers to the effects of global warming on the earth's climate. With improving economic activities and living standards around the globe, people are consuming more goods and services and adding more anthropogenic emissions to the atmosphere. Most greenhouse gases in waste are generated from organic biodegradable waste. $CH_4$ is 25 times more harmful compared to $CO_2$ gas, therefore traps more heat, and also causes global warming and its ill effects. In this comprehensive analysis, multiple IPCC methodologies and first-order decay models were referred to estimate $CH_4$ emission reductions in $tCO_2$ equivalent. The procedure to evaluate the project efficiency includes defining the situations of designed and actual operation capacities, also reflecting possibilities within Bhopal city based on total waste generation in the city. With the recent development in India's carbon mechanisms in order to achieve its NDCs, methane emission reduction estimation potentially plays an important role. Waste generation use and biogas generation are also monitored. This analysis helps us assess the renewable energy potential and methane emission reduction potential of related project operations. Emission reduction through this project activity is 408.3 $tCO_2$e/year for annual average 2TPD biodegradable waste, taking baseline emission from $CH_4$ capture and electricity generation of 100–250 KWh per day in addition to operational use and using this light to power 50 street lights every day.

**Keywords** Emission reduction · Climate change · Environment · Waste management · Biogas · Sustainability

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## 1.1 Introduction

Greenhouse gases such as $CO_2$ and $CH_4$ are climate-forcing factors that drive or force the atmospheric system to change. The recent increase in the number of cyclonic activities in the Indian Ocean region is a clear indication of the ill effects of anthropogenic actions of human beings. The recent disturbance of El Nino and La Nina patterns can also be observed. With the introduction of the Montreal Protocol in 1987, the scientific community tracked down the ill effects of CFCs and by introducing the Kyoto Protocol in 1997 more GHGs are added with the aim of reducing emissions throughout the globe. However, the Kyoto Protocol failed but paved the way for the concept of emission monitoring and helped in the introduction of many carbon credit-based markets; with the Clean Development Mechanism various methodologies are clearly defined in order to promote renewables by providing carbon finance methods of emission reduction. Electricity generation and land use pattern are the major contributor to anthropogenic emissions, and waste management contributes ~5%. Important greenhouse gases with their contribution are $CO_2$—64% followed by $CH_4$—18%, and $N_2O$—6%. Water vapors are not considered in Kyoto but contribute majorly to global warming.

The total annual $CO_2$ emission in India is approximately 2.44 billion $tCO_2e$/year [1]. India's methane emissions in 2016 totaled 409 million $tCO_2e$, of which 73.96% came from the agricultural sector, 14.46% from the waste sector, 10.62% from the energy sector, and 0.96% from industrial processes and product use. 216 WtE facilities with a combined capacity of 370.45 MWeq have been built to produce electricity, biogas/biomethane, and bio-CNG from municipal, industrial, and agricultural solid waste [2]. For several years landfill is the most common, easy, and unavoidable method to tackle waste. However, the recent trend is changing with the help of the Ministry of Environment, Forest, and Climate Change, and the Ministry of New and Renewable Energy via major initiatives like AMRUT and Swachh Bharat Mission. Anaerobic assimilation is a waste administration process for biodegradable materials which produces biogas and a settled processed buildup. Compost, food squander, natural modern waste, and ooze from sewage treatment are broadly utilized in anaerobic digesters (AD) to create biogas made of 50–70% $CH_4$ and 30 to half $CO_2$, with hints of $H_2S$ and $NH_3$ [3]. Accordingly, biogas introduction has diverse GHG moderation influences. Biogas plant life may be the source of enormous fugitive methane emissions. Latest studies have found that methane leaks may additionally originate from various places, inclusive of feedstock storage tanks, fuel safety release valves from the digestion technique, gas storage gadgets, pipework, digestate storage tanks, flaring, foil roofs and wires, and gas engine exhaust [4]. In India, due to insufficient data availability, great uncertainty has been observed regarding the management and emissions of SWDS, making it difficult to estimate the precise value of the GHG emission potential of the landfill. $CH_4$ estimation begins with the experimental setup of the respiration chamber; this is the direct method to quantify $CH_4$ from single cattle; an artificial environmental setup known as chambers is constructed to observe differences in $CH_4$ concentration [5]. Micrometeorological techniques are used to measure

$CH_4$ concentration for a confined geographical area by using a sensor installed at an appropriate height, upstream wind. External tracer can be used to monitor change in concentration of tracer and $CH_4$. By taking measurements of the concentration of background methane combined with downwind measurements of methane alone, methane emissions can also be calculated using inverse dispersion modeling. Recent advancement in technology includes aircraft-based measurements using sensors, and the use of infrared thermography as an indicator for heat and methane production in dairy cattle. Due to its higher accuracy and predictability in $CH_4$ measurements, the respiration chamber technique is still regarded as the gold standard method [6]. The International Panel on Climate Change has established a method for estimating GHGs emitted by landfills that have been widely used by researchers. In this study of Madhya Pradesh, the first biogas plant's biogas is collected from the anaerobic decomposition of wet waste which is generated on a daily basis from adjoining vegetable markets or mandi, and this is used to generate electricity to power streetlights in the vicinity as shown in a process flow diagram. The IPCC pointers describe two main strategies:

(A) The default IPCC methodology that's supported the theoretical gas yield (a mass balance equation).
(B) Theoretical first-order kinetic methodologies, through the IPCC pointers, introduce the "First-Order Decay Model" (FOD).

The main distinction between the above-mentioned methods is that method A describes the exponential decrease of a substance over time whereas decay involves tracking the inflow and outflow rates of a substance to determine its decay in method B [7]. Provided that the yearly amounts associated with the nursing composition of waste disposed of likewise as disposal practices are nearly constant for long periods, the tactic A can turn out fairly sensible estimates of the yearly emissions. Increasing amounts of waste disposed of will cause an overestimation, and decreasing amounts correspondingly an underestimation, of yearly emissions. Methodology B provides a more correct estimate of the yearly emissions. Several countries may, however, have issues obtaining the mandatory knowledge and data (historical data on point disposal, rate constant for the decay) to determine the right basis for emission inventories with acceptable accuracy [8].

## 1.2 Methods

### *1.2.1 Deciding Project Boundary*

The project boundary defines the region inside which emission reductions arise. Emission reductions need to arise at the project or end result from the assignment. In this study, the project boundary includes biogas plants including a digestor and a biogas-based electricity generator. The project boundary shall embody all GHG emissions below the management of the project contributors which can be vast and fair as a result of the CDM project activity. Deciding the project boundary is the initial step to studying emissions in a particular region.

### *1.2.2 Baseline Emission Estimation*

The baseline is the situation that represents the GHG emissions that may occur within the absence of the projected CDM project activity. The project participants will either use the approved methodologies or propose a replacement methodology for determinative baseline scenario. In this study, baseline emission is considered as per IPCC methodology. The default method is based on the equation [3, 8] (see Fig. 1.1):

Methane emissions in biomethanation process (T/year)

$$= (MSW_T * MSW_F * MCF * DOC * DOC_F * F * 16/12 - R) * (1 - OX)$$

where

$MSW_T$: total MSW generated (T/year)

$MSW_F$: fraction of MSW disposed to solid waste disposal sites

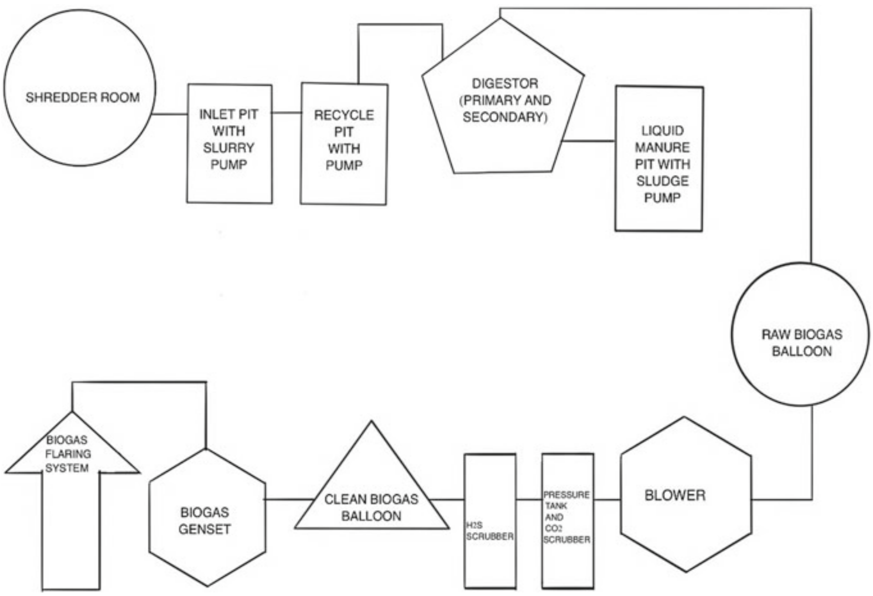


**Fig. 1.1** Process flow diagram of plant

MCF: methane correction factor (fraction)

DOC: degradable organic carbon (fraction) (kg C/kg SW)

$DOC_F$: fraction DOC dissimilated

F: fraction of $CH_4$ in landfill gas (IPCC default is 0.5)

16/12: conversion of C to $CH_4$

R: recovered $CH_4$ (T/year)

OX: oxidation factor (IPCC default is 0).

### *1.2.3 Project Emission*

The project emissions are the one which consist of emission caused by project activities such as diesel or other fossil fuel-based energy consumption in operations of machines and plant; they are further based on electricity consumption, flaring, and methane for digestor; most of the values are taken as standard assumptions of IPCC guidelines based on the scenario [9] (see Fig. 1.2).

**Fig. 1.2** Shredder and Collection by operator. Photograph taken by Authors on 19-10-2021 at biogas plant Bhopal. Released to ICRABR 2022

### *1.2.4 Leakage Emission*

Leakage refers to any GHG emissions that occur outside the project boundary, as a result of the project.

$LE_{AD,y}$ = Leakage emissions associated with the anaerobic digester in year y($tCO_2e$).

$LE_{storage,y}$ = Leakage emissions associated with storage of digestate in year y($tCO_2e$).

$LE_{COMP,y}$ = Leakage emissions associated with composting digestate in year y($tCO_2e$).

In the project's case, $LE_{Storage,y}$ is considered zero as the storage is not un-aerated.

## 1.3 Results

Project activity supports mainly three out of 17 Sustainable Development Goals. SDG 8 Decent work and Economic growth is represented by employing 2 waste collectors and 1 plant manager creating organized sector job, SDGs 7 affordable and clean energy is represented by quantity of biogas captured and used to generate energy and SDG 13 Climate action which is analyzed in this study. Analysis of total GHG emission are quantified based on GHGs emission reduction methodologies of IPCC and total baseline emission is found to be 408.3 $tCO_2e$/year, excluding project emission due to lack of data availability of project emission during the survey. While the net GHG emission reduction due to project activity and leakage emission is taken to be zero. Any emission from wastewater and flaring gas is not considered in this study and is taken to be zero as per methodologies. The daily waste input capacity of the plant is 5 tons per day, however, the annual average amount of waste input is 2 tons per day. As per the design of the plant, biogas must be capable of producing 100–250 units of electricity per day excluding electricity for operational use. One ton of waste can generate 65–80 $m^3$ biogas and a one-meter cube of biogas can produce 1.2–1.3 units of electricity using a single 48 kW or 62.5 KVA natural gas generating model generator. The plant has a digestor of capacity 360 cubic meters with 2 raw biogas collection balloons of 80 cubic meters each, but the plant is operating at very low input due to the effect of the recent pandemic (see Fig. 1.3).

## 1.4 Conclusion

In this study, it can be concluded that similar plants using anaerobic decomposition of biodegradable byproducts can be developed to mitigate $CH_4$ emissions. However significant challenges in quantifying $CH_4$ emission reduction are the monitoring parameters such as feedstock, its quality, and contamination. Based on field visits,

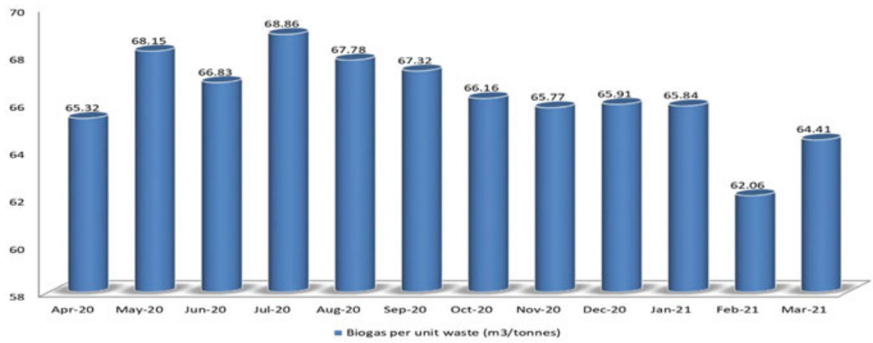


**Fig. 1.3** Biogas generation per unit waste

it was found the capacity of biogas plants gets reduced due to the accumulation of sand and other inert material on the biodigester bed, therefore increasing the cost of maintenance and operations. This biogas plant was operational at a 60% lower functional capacity (5TPD). Since the waste source is only from an adjacent vegetable market, it affected the consumption behavior of the consumers during COVID restrictions.

A significant challenge is the availability of good quality feedstock for which waste transfer stations should work in coordination to provide the required waste within the city. A sustainable circular economy can be created through biomass utilization by recycling organic residues including nutrients in order to bring them back to society as energy and fuel. The uncertainties in the estimates of $CH_4$ emissions from waste are large, no matter the method used. The information on the composition and quantity of waste disposed of at landfills remains usually supported by rough estimates. Statistics on municipal and industrial waste management are presently growing in several countries, and future emissions are based on more reliable data. Due to difference in waste characteristics, SWDS practices involve collecting and selecting emission factors based on the composition of waste, taking into account national circumstances, to ensure clear and comparable coverage of emissions.

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# Chapter 2
# Review of Anaerobic Digestion of Landfill Leachate and its Co-digestion Potential

**Devnita Polley and Sudhir Jain**

**Abstract** A landfill is a cost-effective solution to dispose of municipal solid waste; leachate is its secondary pollutant. Around 60–70% of the municipal solid waste generated in India each day is organic, resulting in a large volume of leachate, which includes a significant quantity of organic matter; anaerobic digestion is a comparatively good treatment option. Landfill leachate characteristics are influenced by the type of trash produced, climatic circumstances, temperature, and other factors and because of the heterogeneous mixture adding co-substrates is a cost-effective option for uniform biogas generation from anaerobic digestion. This paper deals with the various landfill leachate characteristics with anaerobic digestion treatment of mono leachate and its co-digestion potential. Monodigestion of leachate yields 24 L/kgVS of $CH_4$ consumed with 37% of removal efficiency of VS, whereas co-digestion gave a higher $CH_4$ output of 317 L/kg VS consumed with an 80% VS elimination efficiency.

**Keywords** Municipal solid waste · Anaerobic digestion · Landfill leachate · Co-digestion

## 2.1 Introduction

95% of municipal solid waste collected around the world is disposed of in landfills [1]. According to the Central Pollution Control Board (CPCB), India produced 152,076.7 tonnes of municipal solid waste (MSW) per day (TPD) in 2018–2019, with an average waste of 0.11 kg per capita per day, in which only 149,748.6 TPD (80%) was collected, 55,759 TPD (22%) was handled or processed, and roughly 50,161.33 TDP (60–70% organic component) was landfilled [2]. As the organic content is around 60–70% in MSW reported in India, it produces a high amount of leachate consisting of rich organic properties which has the potential to create a considerable quantity of biogas through anaerobic digestion. The biogas generated can be utilised

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for power generation. Biogas generates 2.14 kWh of power per $m^3$ of feed [3]. Not only energy generation, anaerobic digestion has the potential to remediate pollutants such as COD, BOD, TKN, pH, and others [4]. Studies found anaerobic digestion can remove 90% of organic matter and fulfil the conditions set out in the "Municipal Solid Wastes (Management and Handling) Rules, 2016" for the disposal of treated landfill leachates. Monodigestion of leachate yields 350–480 ml/g VS under conventional experimental conditions [5]. By combining landfill leachate with agricultural waste or any other easily biodegradable material, the biomethanation process will be accelerated, resulting in increased methane generation. Co-digestion of landfill leachate with various materials like pineapple peel [5], sugarcane bagasse fly ash [6], and crude residual glycerin [3] has shown good results for biogas production, whereas agricultural waste is abundantly available in India.

Leachate pollutes groundwater as it seeps through the soil. For example, the leachate produced at the Ariyamangalam dumpsite in Tiruchirappalli, Tamil Nadu, India, has significantly affected the groundwater nearby [7]. TDS found in the groundwater is quite higher, and the Cl content is in the higher range. The authors also reported toxic heavy metals in leachate-polluted groundwater, including Pb, Zn, Cu, Mn, and Cd. Therefore, leachate treatment is a significant area of research [7].

Leachate is divided into 3 groups according to its age: young, medium, and old or stabilised leachate [4]. Young leachate is defined as below one year old; medium leachate is defined as one to five years old; and stabilised leachate is defined as over five years old [8]. Stabilised leachate seems to be the hardest to treat out of the three since it breaks slowly, whereas young and medium leachates respond well to biological treatment [9, 10]. In contrast, it is discovered that stabilised leachate can be effectively treated using physicochemical wastewater treatment technologies [7]. However, disposing of the sludge or concentrate left over after leachate treatment is a significant additional challenge. In this paper, the various properties of landfill leachate are presented along with anaerobic digestion potential and co-digestion ability in summarised form.

## 2.2 Landfill Systems

An engineering facility for disposing of MSW that is built and operated with public health and environmental issues in mind is referred to as a sanitary landfill [11]. Monofills are landfills that only accept one type of trash, such as ash, asbestos, and other similar pollutants [12]. Landfills that are utilised to dispose of hazardous materials known as secure landfills. Uncontrolled land disposal sites, sometimes known as waste dumps, are areas where trash is dumped in an unstructured manner on or into the ground [4]. Due to financial restrictions, open dumps are the most common form of MSW disposal in developing nations. Waste is thrown into wetlands for land development in Kolkata, Mumbai, Chennai, and Colombo. Ocean dumping is illegal by legislation in African nations [5]. However, the practice continues to be outlawed in several African coastal cities [4]. Other sophisticated waste disposal methods such as anaerobic digestion, composting, and incineration can be selected based on the kind of waste in Northern European nations such as Germany, where the waste sorting system is quite efficient [4]. Since the previous few decades, there has been an enormous increase in trash production that is correlated with trends in urbanisation and population growth. Management of municipal solid waste (MSW) has become more difficult in India's developing cities. Due to the COVID-19 pandemic in India, there has been a dramatic increase in the production of biomedical waste in recent years, along with exponential population expansion, high urban population density, diversified culture, changing eating habits, and lifestyle changes '[13, 14]. The dynamics of waste creation have evolved over time in "transformed cities," which have experienced fast industrial expansion and population growth over the last. Research has been done in India and across the world to evaluate the severity of soil and groundwater pollution inside and around MSW dumpsites in metropolitan cities to comprehend their detrimental effects on human health [14]. The results of these study activities indisputably show that harmful trace elements, such as As, Cr, Pb, Cu, Ni, Zn, and Hg, are present in both the soil and the groundwater. Heavy metal contamination has already been a significant issue in metropolitan areas [14].

Because of its massive population and growing use of information and communication technologies across all industries, India has an alarmingly high quantity of e-waste. Not only that, but due to urbanisation in rural regions, the number of other electronic devices (such as refrigerators, microwave ovens, air conditioners, colour televisions, DVD players, and MP3 players) are also rising quickly [15]. According to [16], Mumbai leads all other cities in the generation of e-waste. Delhi, Bangalore, Chennai, Kolkata, Ahmedabad, Hyderabad, Pune, Surat, and Nagpur are next in line. About 17 lakh tonnes of e-waste were produced in 2014, according to estimates from the Manufacturer's Association for Information Technology Industry (MAIT) performance annual review [15]. The hazardous waste rule of 1989 states that e-waste should not be considered hazardous until it is established that it has a higher concentration of specific dangerous compounds. Although electronic waste involving PCBs and CRTs invariably exceeds these limits, there are a few grey areas that require attention. India also lacks a suitable, standardised method for disposing of e-waste. Due to this circumstance, the majority of e-waste is dumped in landfills, which causes one of India's fastest-growing environmental problems [16]. The issues are exacerbated by foreign as well as domestic e-waste. Even though the Ministry of Environment and Forest has to give particular approval before importing e-waste, it is getting imported illegally.

Integrated solid waste management (ISWM), 2016, provided a framework to guide the selection of the most appropriate treatment technologies for MSW management. ISWM factories frequently use pre-processing facilities to separate organics from recyclables and other high-calorie waste. A study conducted by CPCB NEERI is presented in Fig. 2.1; from the chart, the fractions of solid waste are seen, and the organic fraction is found to be 47.4%, which is favourable for the MSW to produce a high amount of leachate. Organic waste is degraded aerobically to produce manure or anaerobically to generate power. Ministry of New Renewable Energy, 2021, reported the energy potential of Urban solid waste to be 1247 MW and urban liquid waste

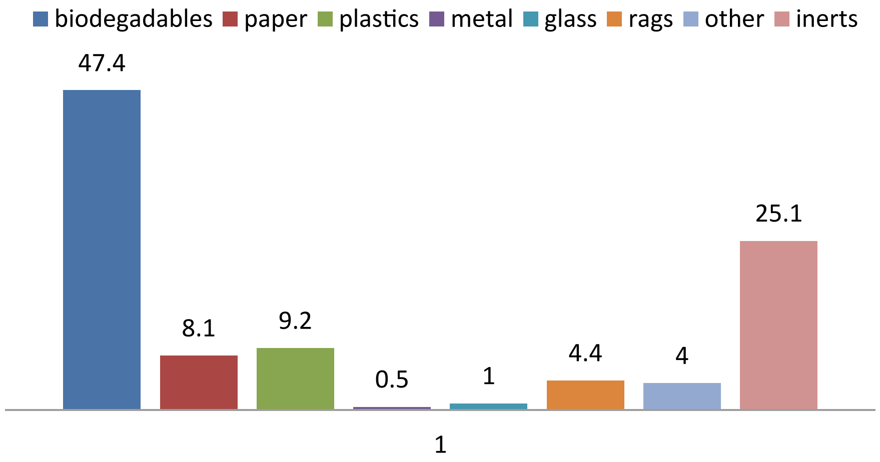


**Fig. 2.1** Typical MSW generation fractions in India. *Source* [18]

to be 375 MW [17]. Separated recyclables are sent to wholesalers for shipment to recycling facilities. High-calorie wastes are baled or processed so that they may be used as fuel or co-processed in cement plants [2].

## 2.3 Landfill Leachate Characteristics

### *2.3.1 Leachate Formation*

The composition of landfill leachate varies greatly depending on the stage of waste development, i.e., aerobic, anaerobic acid, methanogenic, and stabilisation phases [4, 19, 20]. The synthesis of $CO_2$ results from the rapid depletion of $O_2$ during the initial aerobic stage, which occurs in newly dumped waste. The waste's temperature tends to rise in this stage, according to a lot of research [19, 20]. Owing to moisture loss during the compaction and precipitation, a huge volume of leachate is produced during this stage [21]. Once oxygen supplies are reduced enough for fermentation to occur, waste enters the anaerobic phase, also known as the second stage [19, 20]. This stage is dominated by hydrolytic, fermentative, and acetogenic bacteria, which causes a buildup of carboxylic acid and a decrease in pH. This phase is also called acid phase and BOD/COD in this stage is reported to be 0.4–0.7 [19, 20]. The third phase is the methanogenic phase. At the start of this stage, pH of the waste reaches a neutralised level which promotes the development of methanogenic bacteria.

During this stage, bacteria that produce methane convert acids created during the acidic stage into $CH_4$ and $CO_2$, increasing the rate at which methane is produced. During the stable methanogenic phase or stabilisation phase, the rate of methane

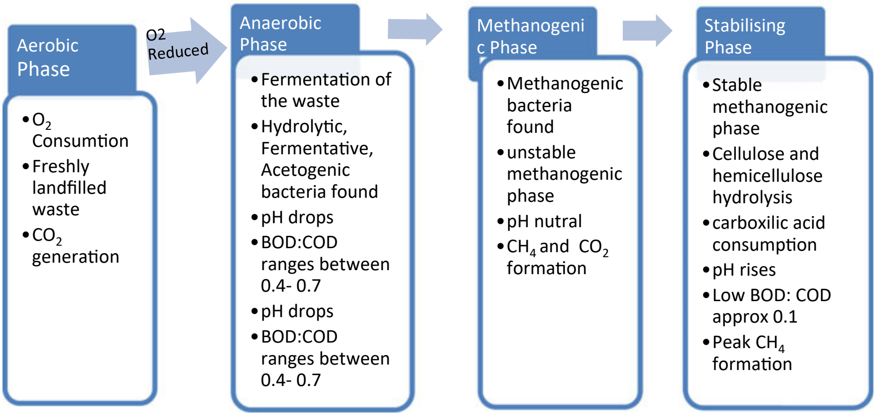


**Fig. 2.2** Leachate formation process in Landfills. *Source* [20]

generation peaks when carboxylic acids decrease, and it starts to slow down. The hydrolysis of cellulose and hemicellulose during the acid phase is proportional to the rate of $CH_4$ production. As pH levels rise, they eventually stabilise at a few milligrammes per litre in a steady state. The BOD: COD ratio frequently falls to as low as 0.1 because carboxylic acid is digested as rapidly as it is produced [19–21]. The leachate formation steps are summarised in Fig. 2.2.

The anaerobic biological conditions are again divided into four phases. The first phase in anaerobic degradation is acid fermentation, which is followed by hydrolysis, acidogenesis, and acetogenesis [12]. Researchers denoted waste age, waste type and content, site hydrogeology, seasonal weather variation, dilution by rainfall, precipitation, and the degree of decomposition within the landfill are all variables that impact the parameters of municipal landfill leachate [4].

### 2.3.2 Leachate Properties

Around 200 toxic chemicals have previously been detected in landfill leachate in previous investigations [22]. Landfill leachate is one of the most complicated wastewaters, containing inorganic salts, heavy metals, a large number of biodegradable organics, and refractory components such as humic compounds, among other things [23].

Leachate contaminants are divided into four categories by Luo et al. [4]: (1) Organic compounds, e.g., BOD, COD; (2) macro inorganic components such as ammonia ($NH_4^+$–N), sodium ($Na^+$), potassium ($K^+$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), manganese ($Mn^{2+}$), iron ($Fe^{2+}$), chloride ($Cl^-$), sulphate ($SO_4^{2-}$), and hydrogen carbonate ($HCO_3^-$); (3) heavy metals such as chromium ($Cr^{3+}$),