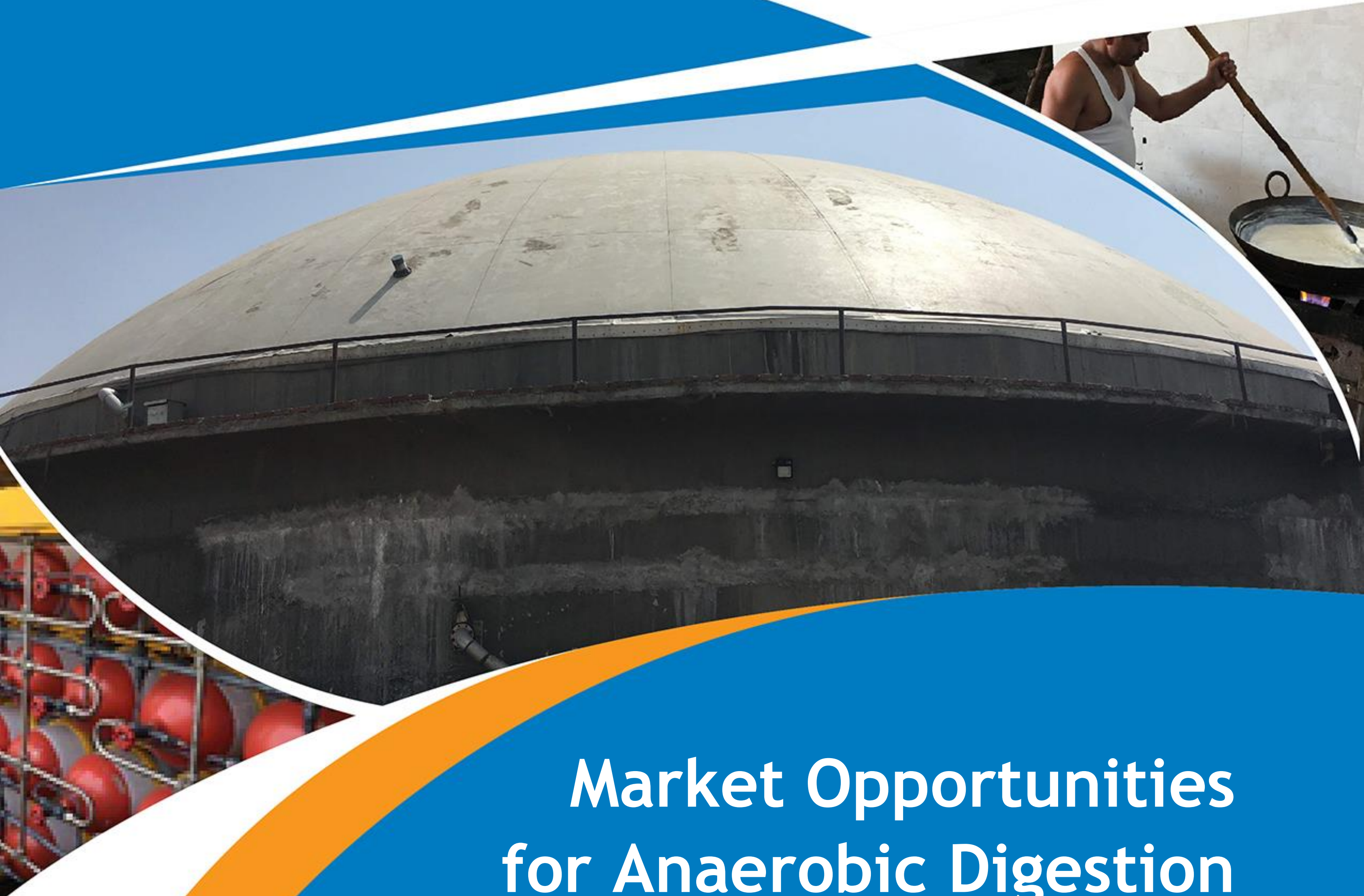


Market Opportunities for Anaerobic Digestion of Livestock and Agro-Industrial Waste in India

Prepared for:

The Global Methane Initiative

February 2020

Table of Contents

Acknowledgements

This report was prepared by the United States Environmental Protection Agency (EPA) on behalf of the Global Methane Initiative (GMI). Abt Associates, The Energy and Resources, Institute, and Eastern Research Group assisted EPA in developing the report under contracts EP-BPA-18-H-0011 and EP-BPA-12-H-0021. We give special thanks to Anil Dhussa for his contributions to the report and insights into India's biogas industry.

Disclaimer

Preface

The Global Methane Initiative (GMI) promotes cost-effective, near-term methane abatement and recovery, and use of methane as a clean energy source. In the agriculture sector, GMI encourages anaerobic digestion (AD) of manure and agro-industrial waste as a method to reduce methane emissions and generate renewable energy.

The **Global Methane Initiative** works in partnership with developed and developing countries, with participation from the private sector, development banks, and nongovernmental organizations. GMI focuses on biogas (produced in the agriculture, municipal solid waste, and wastewater sectors), as well as methane emissions from coal mines and oil and gas systems. Focusing collective efforts on methane sources is a cost-effective approach to reduce greenhouse gas emissions and increase energy security, enhance economic growth, and improve air quality.

Report Overview

Under the auspices of the GMI, the U.S. Environmental Protection Agency developed this market opportunities assessment for biogas from livestock and agro-industrial wastes in India.[1] Recent developments in India that have spurred this effort include but are not limited to:

- Increasing energy demands and growing interest in using renewable energy sources to meet that demand
- Environmental concerns associated with manure and agro-industrial waste management
- New and/or modified national policies supporting AD and renewable energy development
- Opportunities for potential "green" job growth as a result of an expanding AD market.

This market opportunities assessment is geared toward informing project developers, policymakers, and other interested stakeholders about the potential for biogas capture and use in India. It includes the following sections:

- **Uses of Biogas and Digestate**, which describes the uses of biogas as an energy source for multiple purposes, including cooking, transportation, heating, and cooling; and the digestate (leftover material from AD after the feedstock has gone through the digestion phase) as soil amendment, fertilizer, or compost product.
- **Current Biogas Policies and Incentives in India**, which discusses a number of policies and initiatives in effect in India that create an enabling environment for biogas project development. The objectives of the policies vary, including improved manure management, reduced dependence on oil and gas imports, and improved sanitation at the village level. Each of these policies help promote the development of biodigesters to use agricultural waste to produce biogas.
- **Biogas Potential from Agricultural Feedstock**, which provides an overview of the various agricultural feedstocks in India that can be used as input into AD systems, and estimates the potential for methane emissions reduction and methane production for use as an energy source. The sectors discussed include dairy farms, sugarcane processing, distilleries, fruit and vegetable processing, cornstarch production, tapioca production, and milk processing. The goal of this overview is to help industry developers, financiers, and policymakers determine where to focus efforts on biogas development in India.
- **Technology Options**, which identifies the current anaerobic digester technologies used in India. It summarizes the key attributes of anaerobic digesters and identifies small-scale digester technologies used at a household or farm level, followed by medium- and large-scale digester technologies used on a commercial scale. It helps inform project developers and policymakers about the process, types of feedstock, and the scale at which each of these technologies is currently being implemented. It also helps technology providers and project developers understand the technology landscape in India so

[1] This effort is to update a resource assessment that was developed in 2011 (GMI, 2011).

they can consider deployment of alternative technologies used in other countries that may be appropriate for India.

- **Business Models and Case Studies**, which discusses business models, including the key aspects of successful AD systems, potential owner and operator models, and diversification of revenue generation; and provides case studies to highlight successful business models primarily from India.

Reference

GMI. 2011. Resource Assessment for Livestock and Agro-Industrial Wastes – India. Prepared for the Global Methane Initiative by Eastern Research Group, Inc.; TetraTech Consulting Group; and Federation of Indian Chambers of Commerce and Industry. January. Available: https://www.globalmethane.org/documents/ag_india_res_assessment.pdf. Accessed 5/28/2019.

1. Uses of Biogas and Digestate

Anaerobic digesters process feedstock to produce biogas, which consists primarily of methane (40–60 percent) and carbon dioxide. It also includes moisture, hydrogen sulfide, nitrogen, and oxygen. Biogas can be used as an energy source for multiple purposes, including cooking, heating, cooling, transportation, and electricity. Biogas from anaerobic digesters must be cleaned to remove moisture, hydrogen sulfide, nitrogen, and oxygen to be suitable for some uses (e.g., cooking fuel). Additionally, it needs to be upgraded by removing carbon dioxide for other uses (e.g., transportation fuel).

Digestate is the leftover material from anaerobic digestion (AD) after the feedstock has gone through the digestion phase. High solid ("dry") AD systems generate high solid content digestate while low solid ("wet") AD systems generate low solid content digestate. The quality of the digestate depends on the quality of the feedstock. If the feedstock is clean from contamination (toxins, plastics, glass, etc.), the resulting digestate is cleaner and has a better market potential.

1.1 Biogas Use

Cooking

Upgraded or non-upgraded biogas is considered a clean and sustainable cooking fuel, depending on the use. In India, wood-fired stoves and dried cow manure burning are being replaced with biogas cook stoves, improving sanitation and indoor air quality for millions of people. These gas cooking stoves can be connected to small anaerobic digester systems or fueled by bio-compressed natural gas (bio-CNG) in cylinders. Most gas cooking stoves in India currently operate with individual cylinders, while some large cities (e.g., Delhi) have gas pipelines that connect to the stoves. The biogas needs to be upgraded to be fed into such pipelines or compressed into bio-CNG cylinders.

Heating

Biogas can be used directly or with very little conditioning for heat generation and thermal applications. Examples of such uses include:

- Furnaces, dryers, and kilns can use biogas as a replacement for or supplement to conventional fuels in several manufacturing sectors, including cement, brick and ceramics, iron and steel, and wood products.
- Boilers can use biogas as a fuel to produce steam or hot water (e.g., the steam produced by boilers can be used for space heating, process heating, or electricity generation via a steam turbine). Bio-CNG can also be used to fuel furnaces and boilers, or for heating.

Cooling

Small scale famers in India often do not have access to refrigeration technologies, leading to quantities of spoiled agricultural products. Biogas can replace the use of kerosene or liquefied petroleum gas, and be used for cooling as a heat source for vapor absorption refrigerator systems. These systems use locally available farm-based renewable energy sources, including biogas, to run the systems at a much lower operating cost than using diesel or grid electricity. Developed to power cold storage systems to extend the life of perishable agricultural products (e.g., milk, fruits, vegetables), these systems improve economic conditions for farmers in rural areas of India.

Transportation

Biogas that is upgraded to a higher methane purity can be used interchangeably with conventional natural gas. Biogas needs to be upgraded to more than 90 percent methane to be considered useable as a transportation fuel. Biogas can be used as a vehicle fuel when upgraded and compressed into bio-CNG, or liquefied into liquefied natural gas (LNG). Bio-CNG and LNG production are economical only at medium- or large-scale AD facilities due to the costs associated with upgrading technology.

Some cities in India have CNG-powered public transportation vehicles. For example, Delhi currently has over 10,000 CNG buses, and the number of CNG vehicles in India has been increasing. The Government of India plans to develop infrastructure to increase the number of CNG plants, pipelines, and filling stations. It announced an initiative in 2018 to reduce India's dependence on oil and gas imports by producing bio-CNG for transportation fuel using agricultural residues, cattle dung, sugarcane press mud, municipal solid waste, and sewage treatment plant waste.

Electricity Generation

Biogas can be used as a fuel in internal combustion engines or combustion turbines to generate electricity. The electricity can be used to cover onsite energy needs or sold to the local electricity grid. For electricity production, biogas may or may not be additionally cleaned or conditioned, depending on the energy recovery unit installed. The following examples are systems for electricity generation from biogas:

- Internal combustion engines are the most common biogas utilization technology for small to medium-sized AD systems. These engines are available in various sizes, with electrical outputs ranging from a few kilowatts to more than 3.0 MW per unit.
- Gas turbines are generally larger than internal combustion engines and are available in sizes from 1 MW to more than 10 MW. Although smaller gas turbine units or "microturbines" (less than 1 MW) have been used, they are not normally the primary generating unit. Gas turbines are available as modular and packaged systems.
- Combined heat and power (CHP) or cogeneration systems generate electricity and capture waste heat to provide thermal energy. Thermal energy can be used for onsite heating, cooling, or processing needs; or piped to nearby industrial or commercial users to provide a second revenue stream for the project. CHP is often a better economic option for end users located nearby or for projects where the end user has sufficient demand for both electricity and waste heat.

1.2 End Uses of Digestate

Digestate can be used as a soil amendment, fertilizer, or value-added product, most often after post-processing (such as composting). Biogas digester effluents are primarily used as organic fertilizers in India. In some cases, AD systems may sell the digestate as a commercial soil amendment or fertilizer, which can increase the financial viability of the AD system. In the case of some feedstocks (e.g., distillery effluent), the digestate must be further treated or blended before it can be applied on land. In the United States, digestate is often used as animal bedding for cows. New innovations in value-added products such as biodegradable planter pots and building materials are being created from digested manure, providing additional income to the digester owner.

Care should be exercised when using digestate as a fertilizer due to the risk of contamination. The contamination type and level depend on the feedstock and the AD system. With manure and wastewater treatment sludge feedstocks, the biggest risk is pathogen contamination, which can cause serious health issues if applied on agricultural land. Contamination from heavy metals, plastics, and glass is also a challenge when feedstocks are sourced from municipal solid waste.

2. Current Biogas Policies and Incentives in India

India is investing in its national strategy to increase biogas production and reduce methane emissions. Beginning with the Electricity Act of 2003 which promotes generation from non-conventional sources (Government of India, 2005), the biogas strategy includes many policy initiatives, including capacity-building and public-private partnerships, which are spearheaded by different ministries. In addition to the climate benefits of biogas project development, the benefits of this strategy support India's sustainable development goals, including improving sanitation, providing affordable clean energy, and increasing jobs in the green economy.

India's nationally determined contribution as part of the Paris Agreement include a commitment to achieving 40 percent cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030, increase renewable energy capacity from 30 GW by 2016–2017 to 175 GW by 2021–2022, and increase installed capacity of biomass energy from 4.4 GW to 10 GW by 2022 (Union Environment Industry, 2015). Apart from this international commitment, India has also undertaken the Swachh Bharat Mission (Clean India Mission), which is geared toward cleaning India's cities, towns, and rural areas. The effort in rural areas, among addressing other issues, includes efforts to productively use agricultural waste and crop residues to generate biogas.

This section describes the current policies and initiatives that help promote biogas development in India.

2.1 Waste to Energy Program

The Ministry of New and Renewable Energy (MNRE) is the nodal Ministry of the Government of India for all matters related to new and renewable energy. The broad aim of MNRE is to develop and deploy new and renewable energy projects, including biogas, to help meet the energy requirements of the country. MNRE promotes the Waste to Energy Program, a national program that promotes the recovery of energy from urban, industrial, and agricultural wastes through waste-to-energy projects. The program focuses on converting municipal solid waste and agricultural waste into fuel for heating and cooking, combined heat and power, and bio-compressed natural gas (bio-CNG). MNRE has proposed financial incentives to encourage participation in these projects (EAI, 2017), including:

- Financial assistance through interest subsidies for commercial projects, capital cost for innovative demonstration projects that generate power from municipal or industrial waste and sewage treatment plants, and conducting studies on waste-to-energy projects and covering the full cost of such studies
- Incentives to the state nodal agencies for promotion, coordination, and monitoring of waste-to-energy projects
- Promotional activities including research and development, resources assessments, technology upgradation, and performance evaluations.

While there are no limitations on size of the projects, based on the capital subsidy cap for individual projects, projects are typically in the range of 1,200 to 36,000 m^3 biogas/day. In July 2018, MNRE announced the continuation of the program to promote energy from urban, industrial, and agricultural waste and Central Financial Assistance for three fiscal years (2017–2018, 2018–2019, and 2019–2020). The Central Financial Assistance includes a capital subsidy of INR 1.0 crore (approximately USD 150,000) per 12,000 m^3 biogas/day for biogas projects and INR 4.0 crore (USD 600,000) per 4,800 kgs of bio-CNG/day generated from 12,000 m^3 biogas/day. The latter is reduced to INR 3.0 crore if bio-CNG were to be generated from an existing biogas plant. The maximum for any project is INR 10.0 crore (USD 1.5 million).

India's Waste to Energy Program
https://mnre.gov.in/waste-energy https://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf

2.2 Sustainable Alternative Toward Affordable Transportation (SATAT) Initiative

In October 2018, the Union Minister for Petroleum and Natural Gas announced plans to develop bio-CNG plants (Government of India, 2018d). The SATAT Initiative is geared toward reducing India's dependence on oil and gas imports by producing bio-CNG using agricultural residues, cattle dung, sugarcane press mud, municipal solid waste, and sewage treatment plant waste. The Ministry of Petroleum and Natural Gas (MoPNG) anticipates development of 5,000 bio-CNG plants in five years. As part of the initiative, MoPNG guarantees offtake of biogas by publicly owned oil and gas companies and plans to invest INR 175,000 crore (about USD 24 billion) in infrastructure development for bio-CNG distribution as automotive fuel. There is a particular focus on developing bio-CNG using paddy straw with a locational focus in the northern states of Punjab, Haryana, Uttar Pradesh, and Bihar, where 40 million tons of paddy straw is burned every year, causing major environmental and health problems.

This initiative is being implemented in coordination with the public sector undertakings (PSUs) marketing oil and gas, including Indian Oil Corporation, Bharat Petroleum, and Hindustran Petroleum. These PSUs requested letters of intent, in early 2019, from applicants (entrepreneurs, sole proprietorships, partnerships, limited liability partnerships, companies, cooperative societies, and technology providers) to supply bio-CNG. The PSUs assure a purchase price of INR 46 crore per kg of bio-CNG. These facilities are expected to be large-scale projects that can consistently provide bio-CNG as a transportation fuel.

2.3 National Policy on Biofuels

The National Policy on Biofuels (Government of India, Undated), approved on December 24, 2009, aims to ensure that a minimum level of biofuels is available in the market to meet demand at any given time. The policy seeks to elevate biofuels into the mainstream to supplement gasoline and diesel in transportation and stationary applications. This will help ensure energy security, mitigate climate change, create new employment opportunities, and lead to environmentally sustainable development (USDA Foreign Agricultural Service, 2017).

The Government of India announced in 2018 that it proposes to reduce its dependence on crude oil purchases by ten percentage points by 2022. It also aims to achieve 5 percent blending of biodiesel in diesel by 2030 by increasing domestic production of biodiesel, developing new feedstocks and conversion technologies, and creating a suitable environment for biofuels (Government of India, 2018c). This policy includes bio-CNG as an "advanced biofuel" (along with cellulosic ethanol, bio-methanol, drop-in fuels, and algae-based fuels). (Bio-CNG, a renewable form of energy produced from agricultural and food waste, is a purified form of biogas with over 95 percent pure methane gas.) The National Policy on Biofuels includes provisions for financing as well as financial and fiscal incentives.

India's National Policy on Biofuels
https://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf

2.4 Galvanizing Organic Bio-Agro Resources (GOBAR)-DHAN

Livestock waste management in India can result in air pollution and associated health impacts when cattle manure is dried and used as a cooking fuel. Poor sanitation practices from manure discarded in open spaces results in land and water pollution and health impacts due to pathogens. GOBAR-DHAN is an effort to create clean villages in India by using livestock manure and solid agricultural waste to produce biogas or bio-CNG.

This effort, led by the Ministry of Drinking Water and Sanitation (MDWS), is an extension of the Swachh Bharat Mission. It aims to help villages manage their bio-waste and educate people about the importance of safe and efficient bio-agro waste management. MDWS aims to establish 700 small scale and community scale bio-agro waste management projects in about 350 Districts from 2018 to 2019. The scheme will be implemented in two phases, with half of the projects in the first half of the year and the remainder in the second half (Government of India, 2018a). In addition to providing energy and improving sanitation, GOBAR-DHAN will benefit villages in several ways, including:

- Providing organic fertilizer for farmers
- Reducing insect-borne diseases, including malaria, by decreasing waste stagnation
- Improving indoor air quality by reducing reliance on dung cakes and firewood
- Creating green jobs such as waste collection and transportation, plant operation and maintenance, and biogas distribution
- Reducing the burden of firewood and dung cake collection on women.

States can choose to develop as many viable projects as possible to achieve effective bio-waste management in their villages. Funding under the initiative will be based on the number of households in each Gram Panchayat (village or small town with local government) and the chosen model of operation. Villages with up to 150 households will be eligible for a maximum of INR 3.5 lakh, villages of 300 households will be eligible for up to INR 6 lakh, villages up to 500 households will be eligible for up to INR 7.5 lakh, and villages of 500 or more households will be eligible for up to INR 10 lakh. Villages cannot receive GOBAR-DHAN funding if they have used funding for other solid and liquid waste management projects under the Swachh Bharat Mission.

The GOBAR-DHAN Initiative
http://drsjk.jk.gov.in/pdf/GOBAR%20DHAN%20guidelines.pdf

2.5 National Biogas and Manure Management Program (NBMMP)

NBMMP, first implemented in 1981 by MNRE, promotes the use of biogas plants based on cattle manure and other organic waste. NBMMP has helped establish small-scale biogas plants that families in rural areas can use to obtain cooking fuel and organic fertilizer. In 2018, MNRE announced that it aimed to produce at least 255,000 (2.55 lakh) biogas plants by the end of 2020 in the capacity range of 1 m^3 to 24 m^3 per day (Government of India, 2018b).

State nodal departments and agencies, as well as the Khadi and Village Industries Commission (KVIC), implement the program. These organizations also employ their state- or district-level institutions, and trained turn-key workers and rural entrepreneurs to help implement the program. Additionally, the local governments (Panchayats) help select beneficiaries and monitor the program. Thirteen Biogas Development and Training Centers have been established in various universities, Indian Institutes of Technology, and other technical institutes to provide training and technical support (Venkateswara and Sundar Baral, 2013).

India's National Biogas and Manure Management Program
https://mnre.gov.in/biogas

2.6 Electricity Act

The Electricity Act of 2003 (Dhussa, 2008) helps State Electricity Regulatory Commissions promote co-generation and generation of electricity from non-conventional sources (Government of India, 2005). It includes provisions for government support of biogas in India. These provisions include open access to the grid for renewable sources of power, preferential tariffs by state regulators, targets for renewable energy, and decontrolled captive generation.

India's National Electricity Policy
https://powermin.nic.in/en/content/national-electricity-policy

2.7 Companies Act of 2013

The Companies Act was originally passed by the Parliament of India in 1956 and is implemented by the Indian Ministry of Corporate Affairs. Under the Companies Act of 2013, companies having a certain level of profits are directed to spend 2 percent of their average annual net profit on Corporate Social Responsibility (CSR) activities. The profit thresholds include a net worth greater than rupees 500 crore (72.7 million USD), a turnover of rupees 1,000 crore (145.4 million USD), or an annual net profit of rupees 5 crore (727,300 USD) or more (Government of India, 2013; PwC India, 2013). Estimates indicate that a fair share of the available CSR funding of about INR 220 billion (USD 3.5 billion) annually will be invested in environment initiatives. This funding may be used to support biogas projects.

India's Companies Act of 2013
http://www.mca.gov.in/Ministry/pdf/CompaniesAct2013.pdf

2.8 References

Dhussa, A. 2008. Biogas in India. Ministry of New and Renewable Energy, Government of India, New Delhi. Methane to Markets Partnership. September 12. Available: *http://www.iiec.org/document-library/iiec-project-publication/proceedings/usaid-methane-to-markets-grant/3-biomethanation-initiative-of-mnre-anil-dhussa-mnre/file. Accessed 5/28/2019.*

EAI. 2017. Indian Government Support for Waste to Energy Projects. Latest News for Energy Efficiency, Solar, Wind, Biomass Power, Biofuels, Waste to Energy. Energy Alternatives India. Available: *http://www.eai.in/ref/ae/wte/pol/policies.html. Accessed 5/28/2019.*

Government of India. 2005. National Electricity Policy. Resolution No. 23/40/2004-R&R (Vol. II). The Gazette of India. February 12. Available: *https://powermin.nic.in/en/content/national-electricity-policy. Accessed 5/28/2019.*

Government of India. 2013. The Companies Act, 2013. Available: *http://www.mca.gov.in/Ministry/pdf/CompaniesAct2013.pdf. Accessed 5/28/2019.*

Government of India. 2018a. Guidelines for GOBAR-DHAN. Government of India, Ministry of Drinking Water and Sanitation. April.

Government of India. 2018b. E-File No. 253/16/2017-BIOGAS. Government of India, Ministry of New and Renewable Energy (Biogas Technology Development Group). May.

Government of India. 2018c. No. P-13032(16)/18/2017-CC. Ministry of Petroleum and Natural Gas Notification. *The Gazette of India*. June 2018.

Government of India. 2018d. Petroleum Minister Launches SATAT Initiative to Promote Compressed Bio-Gas as an Alternative, Green Transport Fuel, Press Information Bureau, Government of India, Ministry of Petroleum & Natural Gas. October 1. Available: *http://pib.nic.in/newsite/PrintRelease.aspx?relid=183842. Accessed 5/28/2019.*

Government of India. Undated. National Policy on Biofuels. Available: *https://mnre.gov.in/file-manager/UserFiles/biofuel_policy.pdf. Accessed 5/28/2019.*

PwC India. 2013. Companies Act, 2015. Key Highlights and Analysis. PricewaterhouseCoopers Private Limited. November 30. Available: *https://www.pwc.in/assets/pdfs/publications/2013/companies-act-2013-key-highlights-and-analysis.pdf. Accessed 5/28/2019.*

Union Environment Industry. 2015. India's Intended Nationally Determined Contribution: Working Towards Climate Justice. Available: *https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/India%20First/INDIA%20INDC%20TO%20UNFCCC.pdf. Accessed 5/28/2019.*

USDA Foreign Agricultural Service. 2017. India Biofuels Annual 2017. Global Agricultural Information Network GAIN Report Number: IN7075. June 27. Available: *https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf. Accessed 5/28/2019.*

Venkateswara, R. and S. Sundar Baral. 2013. Biogas in India. *Renewable Energy Akshay Urja 50(6):48–51.* Available: *https://mnre.gov.in/file-manager/akshay-urja/march-june-2013/EN/48-51r.pdf. Accessed 5/28/2019.*

3. Biogas Potential from Agricultural Feedstocks

Agriculture in India is the means of livelihood for almost two-thirds of the work force in the country, with more than 600 million people involved in agriculture or agriculture-related activities. With 168 million hectares of arable land, India ranks second only to the United States in the amount of arable land. India has more than 500 million head of livestock and 700 million head of poultry (Government of India, 2014). With this level of agricultural activity, there is substantial amount of waste produced that could serve as feedstock for biogas production through anaerobic digestion (AD). Agricultural waste is produced from a wide range of subsectors, including crop production, livestock and milk production, and agro-based industries (paper and pulp production, sugarcane processing, distilleries, and other food and food processing industries).

In 2010, emissions of greenhouse gases (GHGs; excluding the land use and forestry sectors) in India were 2.7 billion metric tons of carbon dioxide equivalent (CO_2e). Nearly a quarter of these emissions were from agriculture, with an additional 5 percent from waste (including solid waste, wastewater, and waste incineration). Figure 1 presents national GHG emissions data for India.

The purpose of this section is to describe the availability of feedstocks for AD, as well as their associated methane reduction potential and biogas production potential. The goal of this overview is to help industry developers, financiers, and policymakers determine where to focus efforts on biogas development in India.

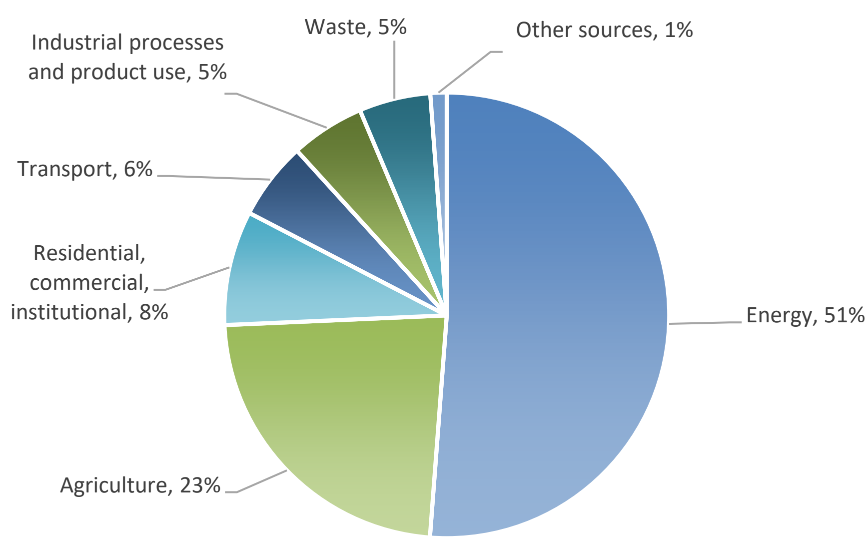


Figure 1. Total 2010 GHG Emissions in India by Sector (FAO, 2018)

3.1 Overview of Reviewed Agriculture Sectors

Subsectors of livestock production and agricultural commodity processing that had the greatest potential for biogas capture and use through AD were previously identified for India in the *Resource Assessment for Livestock and Agro-Industrial Wastes – India* (GMI, 2011). These subsectors included dairy farms, sugarcane processing, distilleries, fruit and vegetable processing, cornstarch production, tapioca production, and milk processing. The Global Methane Initiative (GMI) has included poultry manure and crop residues in this report based on increased interest in AD of poultry manure in India, primarily related to environmental concerns with poultry manure management and the air pollution and health impacts of burning crop residues, primarily rice paddy straw.

Table 1 below briefly describes each subsector included in this section and its primary geographic location. The remainder of this section includes a more detailed discussion of each of these subsectors.

Table 1. Main Subsectors with Potential for Methane Emission Reductions

Subsector	Agricultural Production	Primary States
Dairy Farms	67.5 million head of milk-producing cattle and 51.1 million head of milk-producing buffalo in 2012 (Government of India, 2014)	Uttar Pradesh, Madhya Pradesh, Rajasthan, West Bengal, Maharashtra
Poultry Farms	729 million head of poultry in 2012 (Government of India, 2014)	Andhra Pradesh (including Telangana), Tamil Nadu, Maharashtra
Milk Processing	165 million metric tons of milk produced in 2016–2017, 20 percent of which was processed (Government of India, Undated)	Uttar Pradesh, Rajasthan, Madhya Pradesh, Gujarat, Andhra Pradesh
Sugarcane Processing	348 million metric tons of sugarcane produced in 2014 (Government of India, 2018)	Maharashtra, Uttar Pradesh, Andhra Pradesh, Karnataka, Tamil Nadu, Gujarat
Distilleries	4.5 billion liters of alcohol produced	Maharashtra, Uttar Pradesh, Andhra Pradesh, Karnataka, Tamil Nadu, Gujarat
Fruit and Vegetable Processing	97 million metric tons of fruits and 184 million metric tons of vegetables produced in 2016–2017, 2 percent of which was processed (Government of India, 2018; USDA GAIN 2017b)	Karnataka, Maharashtra, Andhra Pradesh, Punjab, Gujarat
Cornstarch Processing	1.8 million metric tons of cornstarch from 24 million metric tons of corn (USDA GAIN 2017c)	Andhra Pradesh, Karnataka, Gujarat, Uttarakhand
Tapioca Processing	79 thousand metric tons of tapioca from 4.9 million metric tons of cassava produced in 2013–2014 (Government of India, 2018)	Kerala, Tamil Nadu, Andhra Pradesh
Crop Residues	178 million metric tons of surplus crop residue not used for other purposes (TIFAC, 2018)	Uttar Pradesh, Punjab, Maharashtra, Andhra Pradesh, Gujarat, Madhya Pradesh, Haryana, Telengana, Karnataka

Biogas Production Potential

AD systems can produce biogas and reduce methane gas emissions from the existing, or baseline, waste management system; and provide an opportunity to generate revenue from the produced biogas.

Biogas production and methane emission reduction potentials are defined as follows:

- **Biogas production potential** represents the amount of biogas that may be produced from AD systems.
- **Direct methane emission reduction potential** represents the methane emissions that may be avoided due to the use of AD systems. Direct emission reduction potential is reported here both in terms of CH_4 and CO_2e.
- **Indirect emission reduction potential** represents the CO_2e emissions that could be avoided if biogas were used as a fuel for electricity generation in place of fossil fuels.

Table 2 presents estimates of the potential methane emission reductions and biogas productions for the subsectors reviewed in this report. Default values from the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC 2006 Guidelines)* were used for the calculations when country-specific data were not available. Appendix A presents details of the calculations.

Table 2. Biogas Potential By Subsector

	Biogas Production Potential (million m^3/yr)	Direct Methane Emission Reduction Potentials		Indirect Emission Reduction Potential
		CH_4 (thousand metric tons/yr)	CO_2e (thousand metric tons/yr)	CO_2e (thousand metric tons/yr)
Dairy Manure	5,137	324	8,096	12,788
Poultry Manure	929	3.3	81.4	1,573
Sugarcane Processing	328	122	3,062	554
Distilleries	125	8.8	220	212
Milk Processing	17	1.2	29	28
Fruit and Vegetable Processing	27	10	254	46
Cornstarch Processing	13	5	126	23
Tapioca Processing	0.3	0.1	2.9	0.5
Crop Residues	29,983	na	na	Na
Total	**38,538**	**359**	**8,975**	**15,224**

Notes:

1. Totals may not sum due to rounding.
2. Direct methane emission reduction potential was not calculated since the burning of crop residues does not produce methane and GMI lacked data on how the remainder of the surplus crops are disposed of.

While these industries may produce significant quantities of solid waste that could potentially be added to AD systems, these wastes were not included in developing the estimates shown in Table 2 due to lack of available data. However, the addition of these wastes may significantly increase the methane generation of the AD system.

Codigestion

Codigestion occurs when more than one type of organic waste is fed into an anaerobic digester. Codigestion typically is used to manage multiple waste streams and increase the volume of biogas produced. The wastes discussed above could be codigested resulting in higher methane production potentials than presented in Table 2.

Ideal feedstocks for codigestion are those that have a high biogas yield. Since it will impact the amount and nature of the feedstock to be digested, the following considerations need to be evaluated when determining if codigestion is an option:

- Volume of additional feedstock
- Impact of additional feedstock
- Potential for the introduction of toxic substances that will suppress biogas production
- Ability to utilize the additional biogas produced
- Possible need for pre-processing of the additional waste
- Need for additional digester effluent disposal
- Ability to secure a long-term contract with the supplier guaranteeing minimum volume, quality, and fees of feedstock.

3.2 Dairy Manure

Sector Description

India is the largest producer of milk in the world, with a population of milk-producing buffalo, cattle, and goats of more than 180 million head. According to the 19th Livestock Census (Government of India, 2014), India has 67.5 million milch (milk producing) cattle, including both dry and in-milk females, and 51.1 million milch buffalo. These animals are concentrated in several states. More than 50 percent of India's dairy cattle population is concentrated in Uttar Pradesh, Madhya Pradesh, Rajasthan, West Bengal, Maharashtra, and Bihar. Uttar Pradesh, Rajasthan, and Andhra Pradesh (including Telangana) together have 50 percent of India's dairy buffalo population. Figure 2 presents a map of the top dairy-producing states, shown in dark blue, from the combination of dairy and buffalo.

As seen in Figure 3, the top 10 states with the greatest dairy cattle populations account for over three-quarters of dairy cattle in India.

Figure 2. Main Dairy-Producing States

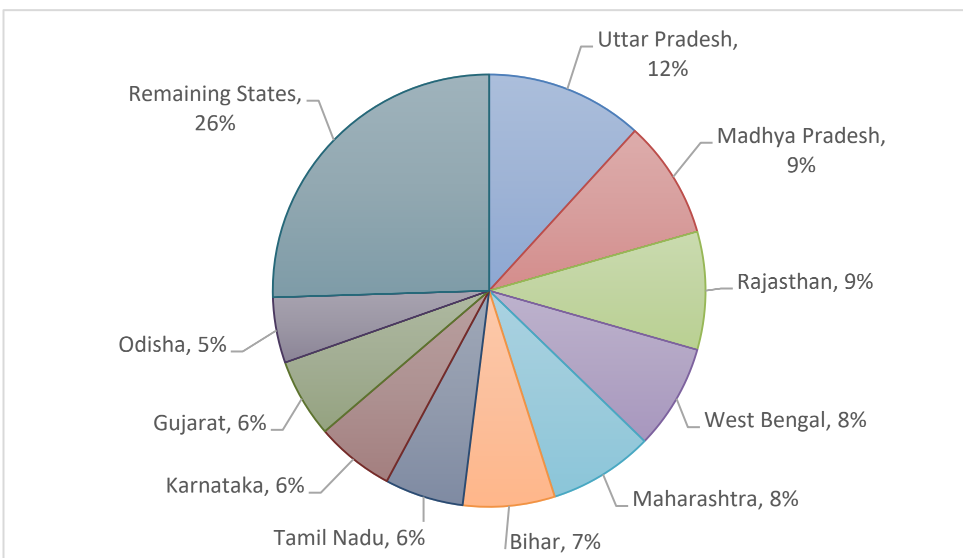


Figure 3. Dairy Cattle Population from the 19th Livestock Census (Government of India, 2014)

Manure Management

Based on assumptions in the *IPCC 2006 Guidelines*, 51 percent of dairy manure (both cattle and buffalo) in India is burnt for fuel, 27 percent is left on pasture, 19 percent is spread daily, 1 percent is managed in liquid slurry systems, and the remaining 1 percent is managed in AD systems.

Biogas Production Potential

For the assessment, GMI assumed that 50 percent of dairy manure managed on systems other than pasture could be treated using AD, based on expert judgment. Table 3 presents the biogas production and methane emission reduction potentials for dairy manure. Default values from the *IPCC 2006 Guidelines* were used to calculate the values included in the table. Appendix A presents details of the calculations.

Table 3. Biogas Production and Direct Methane Emission Reduction Potential for Dairy Manure in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	5,137
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	324
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	8,096
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	12,788

3.3 Poultry Manure

Sector Description

Poultry production is one of the fastest-growing agricultural sectors in India. Between 2007 and 2012, the population of poultry animals in India increased by 12 percent from 648 to 729 million head.

Chickens or fowls (including laying hens and broilers) make up the majority of poultry in India. The remaining poultry (ducks, turkeys, and others), make up about 5 percent of the population.

India's primary poultry-producing states, Andhra Pradesh (including Telangana), Tamil Nadu, and Maharashtra, contain nearly 50 percent of the country's total poultry population. Figure 4 presents a map with the main poultry-production states shown in dark blue. Figure 5 presents the top 10 poultry-producing states and their populations.

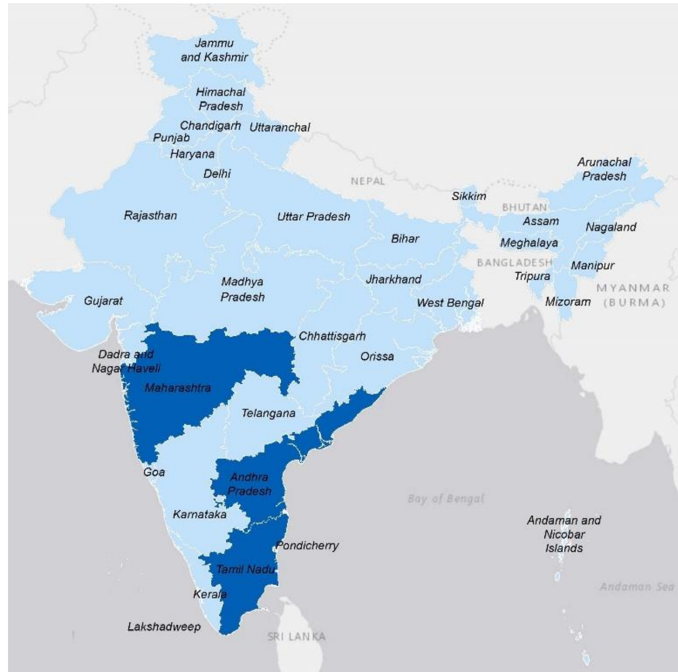


Figure 4. Main Poultry-Producing States

Manure Management

The production and development of poultry produces waste, which is called "litter" and includes manure, eggshells, feathers, and feed. This waste does not typically include any bedding material because it is generally not used in India. Relatively few poultry farms use any type of anaerobic treatment. At most poultry farms (and likely all large poultry farms), the litter is typically removed from the animal housing every six months and composted for use as fertilizer.

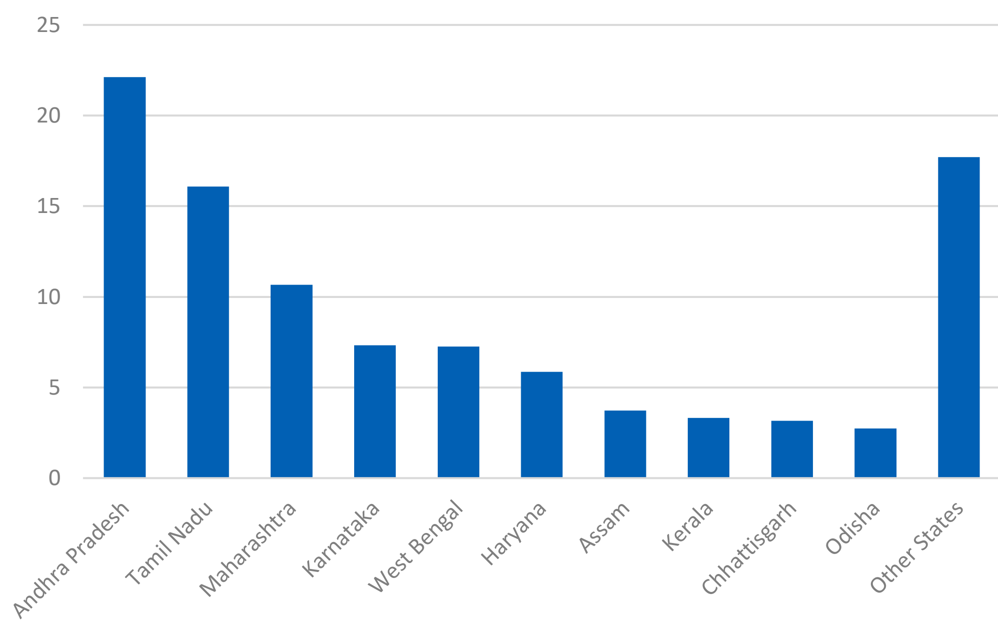


Figure 5. Poultry Population by State (percent)
(Government of India, 2014)

Biogas Production Potential

AD of poultry manure can be a challenge due to the moisture and nitrogen content of the waste, and the presence of a significant amount of grit. Also, poultry manure typically has relatively low methane emissions and low methane production potential compared to other types of manure. This is especially true when the poultry manure is mixed with other materials (such as feathers) and not removed from the animal housing frequently.

However, due to negative environmental impacts of poultry manure in India, there is interest in using AD for poultry manure management. Multiple Indian poultry farmers have installed AD systems. Some of these systems modified existing manure handling and management practices. For example, the Radu Sakku Agro Farm in Karlam village in the state of Andhra Pradesh installed conveyor belts to remove manure daily from the poultry housing; this manure was then transported to an AD system (Srinivas, 2013).

For this assessment, GMI assumed that 50 percent of poultry manure could be treated using AD, based on expert judgment. Table 4 presents the biogas production and methane emission reduction potentials for poultry manure. Default values from the *IPCC 2006 Guidelines* were used to calculate these numbers. Appendix A presents details of the calculations.

Table 4. Biogas Production and Direct Methane Emission Reduction Potential for Poultry Manure in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	929
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	3.3
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	81.4
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	1,573

3.4 Sugarcane Processing

Sector Description

India is the largest consumer and second-largest producer of sugar worldwide with sugarcane grown across India. Uttar Pradesh, Maharashtra, Andhra Pradesh, Karnataka, Gujrat, and Tamil Nadu are the primary sugar-producing regions, as shown in Figure 6.

Figure 6. Main Sugar-Producing States

Sugar processing facilities tend to be located near major sugarcane-producing areas to minimize transportation costs. As a result, Uttar Pradesh, Maharashtra, Karnataka, and Tamil Nadu have the highest amount of both sugarcane area and sugarcane production (VSI, 2018). As presented in Figure 7, these states make up nearly 85 percent of sugarcane production in India. Based on expert judgment, an estimated 75 percent of sugarcane is processed in sugar mills, while the remaining 25 percent is used to produce jaggery, an unrefined sugar product, which produces no wastewater.

In the 2011–2012 processing season, 529 sugar factories were operational in India and processed 257 million metric tons of sugarcane, producing 26 million metric tons of sugar (VSI, 2018). As of 2014, the amount of sugarcane processed was over 350 million metric tons.

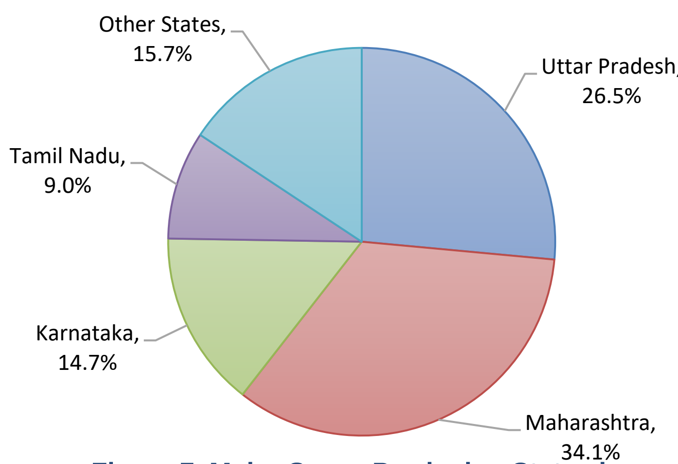


Figure 7. Major Sugar-Producing States by Percent of Production (VSI, 2018)

Wastewater Treatment

Waste products from sugarcane mills include bagasse (residue from the sugarcane crushing), press mud (soil and other foreign material separated by juice clarification), and wastewater (from washings). Based on the IPCC methodology, wastewater emissions are related to the chemical oxygen demand (COD) content of wastewater. Typical sugarcane mill wastewater has a COD that can be as high 32,000 mg/L; however, on average, the COD is closer to 3,000 mg/L (GMI, 2011). For this assessment, GMI used the IPCC default COD of 3,200 mg/L.

Based on information collected during the development of the 2011 Resource Assessment for India, sugarcane processing facilities commonly use a combination of aerobic and anaerobic treatments. Aerobic treatment is the most common management practice, followed by AD. An additional 17 percent of facilities combine aerobic treatment with AD.

Biogas Production Potential

For this assessment, GMI assumed that 5 percent of sugar processing wastewater is managed in open lagoons that could be converted to AD systems (as determined from information collected for the 2011 India Resource Assessment). Table 5 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 5. Direct Methane Reduction and Methane Production Potential for Sugar Processing in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	328
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	122
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	3,062
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	554

3.5 Distilleries

Sector Description

There are 330 distilleries in India that produce 4.5 billion liters of alcohol annually (USDA GAIN, 2017a). Molasses produced as the byproduct of sugarcane refining is the major feedstock for distilleries. As a result, distilleries are often, but not always, integrated with sugarcane processing mills. A minor number of distilleries use grain as a feedstock (ENVIS Centre, Undated).

Distilleries are typically located in or near the major sugarcane-producing areas in India to minimize raw cane and molasses transportation costs. As a result, similar to sugarcane processing facilities, distilleries are primarily located in Maharashtra, Uttar Pradesh, and Tamil Nadu. The main producing states are shown in dark blue in Figure 8.

Figure 8. Main Alcohol-Producing States

Wastewater Treatment

Major sources of wastewater for molasses-based distilleries include process waste streams like spent wash, fermented sludge, and spent lees. Non-process waste streams that produce significant quantities of wastewater include cooling water, waste wash water, boiler blowdown, and bottling plant wastewater (ENVIS Centre, Undated). Nearly 12–15 L of wastewater is produced per liter of alcohol generated, and COD can range from 80,000 to 160,000 mg/L (ENVIS Centre, Undated).

Based on expert opinion, more than 90 percent of distilleries in India already treat their wastewater with AD systems. In distilleries without AD, incineration is another common method of waste disposal.

Biogas Production Potential

Approximately 5 percent of distillery wastewater in India is currently managed in aerobic systems. For this assessment, GMI assumed that the wastewater managed in aerobic systems could instead be managed using AD systems. Table 6 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 6. Biogas Production and Direct Methane Emission Reduction Potential for Distilleries in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	125
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	8.8
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	220
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	212

3.6 Milk Processing

Sector Description

India is the world's largest milk producer with more than 165 million metric tons of milk produced in the 2016–2017 market year (Government of India, Undated). Figure 9 presents a map of the main milk-producing states, shown in dark blue, which mainly track the location of dairy cattle discussed in Section 2.1. Figure 10 presents the top 10 milk-producing states in 2017, which accounted for greater than 80 percent of production.

India's milk production has been continuously increasing due to its growing livestock population, better feedstocks, and better breeds of cattle. In the 2016–2017 market year, Uttar Pradesh, Rajasthan, Madhya Pradesh, Gujarat, and Andhra Pradesh were the major milk-producing states, accounting for greater than 50 percent of the nation's milk production. Figure 11 (Government of India, Undated) shows the increase in milk production in India over 30 years.

Figure 9. Main Milk-Producing States

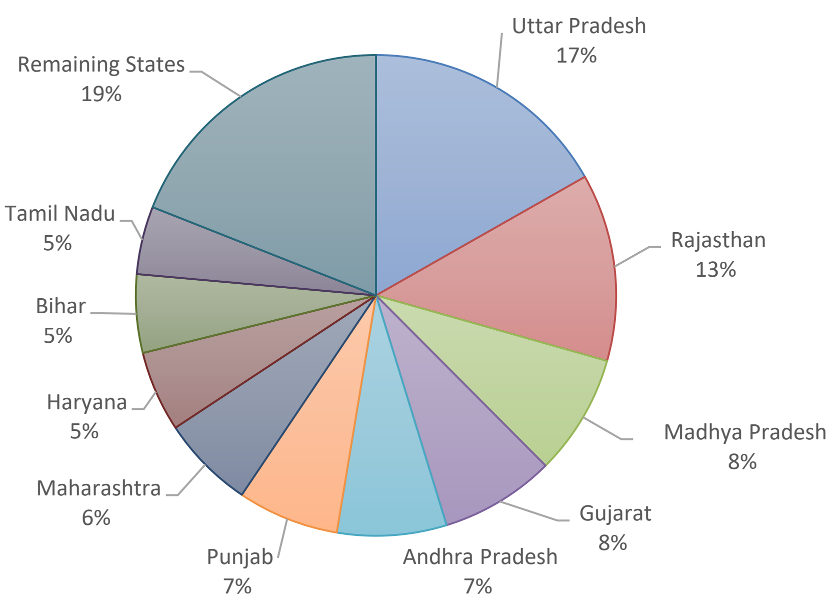


Figure 10. Milk Production for the 2016–2017 Market Year (National Dairy Development Board, 2017)

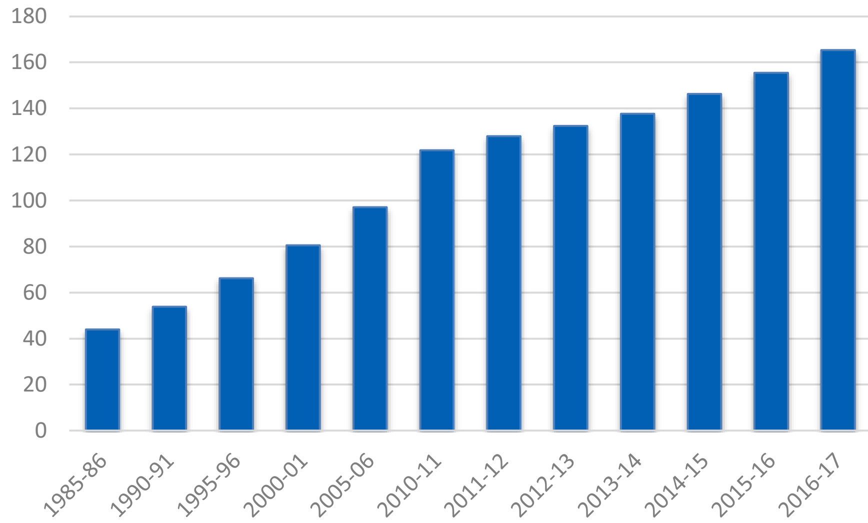


Figure 11. Milk Production in India in Million Metric Tons (DAHDF, 2017)

Wastewater Treatment

About 20 percent of milk produced in India is processed (Mehrotra et al., 2016). Water is used in milk-processing plants for cleaning equipment and chilling, and during processing. Water used for cooling is reused and segregated from the water used for milk processing. In general, the ratio of fresh water used for milk processing is around 1:1, and the amount of wastewater generated is usually 75 to 85 percent of the water used, depending on the dairy product. Based on the IPCC methodology, methane emissions from wastewater are based on the amount of COD content. The COD at milk processing plants in India typically ranges from 1,000 to 4,500 mg/L (Mehrotra et al., 2016).

Milk-processing plants in India have wastewater treatment systems that meet the regulatory requirements of the Central Pollution Control Board and remove high levels of suspended solids and organic material. Most milk processing wastewater is managed using aerobic treatment. Few AD systems treat dairy processing waste.

Biogas Production Potential

For this assessment, GMI assumed that 5 percent of the wastewater from milk-processing facilities could be managed using AD systems, based on expert judgment. Table 7 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 7. Biogas Production and Direct Methane Reduction Potential for Milk Processing in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	17
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	1.2
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	29
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	28

3.7 Fruit and Vegetable Processing

Sector Description

In the 2014–2015 market year, an estimated 97.4 million metric tons of fruits and 184.4 million metric tons of vegetables were produced in India (Government of India, 2018). An estimated 2 percent of the fruit and vegetable production is processed (USDA GAIN, 2017b). Typical processed products include fruit pulps, juices, pickles, dehydrated and curried vegetables, dried fruits, and processed mushrooms (USDA GAIN, 2017b).

Figure 12 highlights the main states producing fruits and vegetables in India, and Table 8 presents the fruit and vegetable produced in these states.

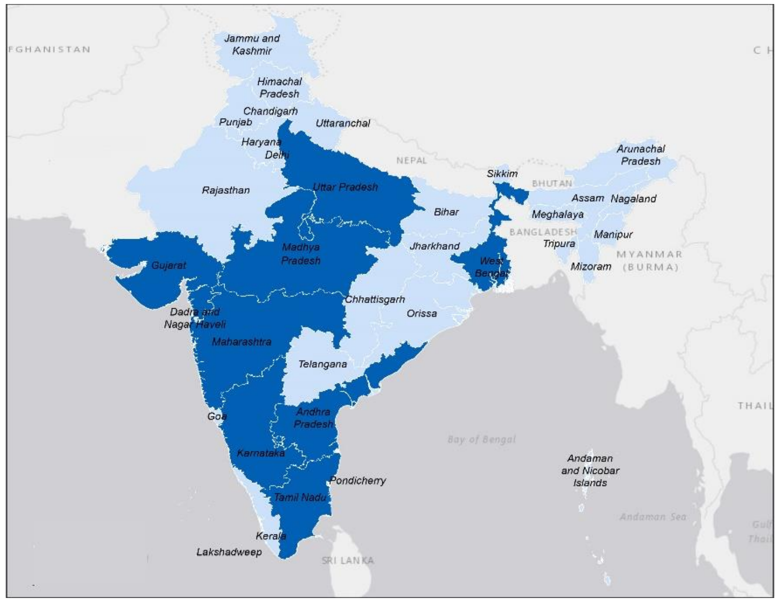


Figure 12. Main Fruit and Vegetable-Producing States

Table 8. Major Indian States Contributing to Fruit and Vegetable Production

State	Fruit/Vegetable Production
Andhra Pradesh	Mango, tomato, chilis, turmeric
Uttar Pradesh	Mango, potato
Gujarat	Onion, potato, banana, mango
Maharashtra	Grapes, mango, banana
Karnataka	Citrus fruits, grapes, mango
Tamil Nadu	Guava, banana, mango
West Bengal	Brinjal, cabbage, potato, mango
Madhya Pradesh	Temperate fruits, apple, pear, plum, peach

Source: Government of India, 2017.

Wastewater Treatment

Fruit and vegetable processing produces a significant amount of liquid waste with high concentrations of organic matter. While wastewater type and composition vary by type of product, processes that may contribute to wastewater production at food processing facilities include washing, husking, desilking, blanching, cutting, peeling, slicing, clipping, screening, and grading.

Preliminary treatment of wastewater may include screening and grit removal, which is typically followed by pH adjustment and aerobic treatment. Although aerobic biological treatment is the most common practice, variable flow rates and concentrations of organic compounds result in operational problems and variations in effluent quality. As a result, anaerobic processes are becoming the preferred approach for treating fruit and vegetable processing wastewater in India. Of the 18 percent of wastewater being managed in anaerobic systems, it is estimated that half is managed in open lagoons (GMI, 2011).

Biogas Production Potential

For this assessment, GMI assumed that the 9 percent of wastewater managed in open lagoons could be replaced with and managed using AD systems, based on expert judgement. Wastewater that is managed in open lagoons typically has the greatest potential for reducing methane emissions. Table 9 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 9. Biogas Production and Direct Methane Emission Reduction Potential for Fruit and Vegetable Processing in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	27
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	10
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	254
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	46

3.8 Cornstarch Production

Sector Description

The growth of the starch industry in India has been driven by population growth and the increase in disposable income. Corn is one of the primary sources of starch in India. Cornstarch is widely used in foods, but also has applications in the paper and textile industries.

India produced 24 million metric tons of corn during the 2016–2017 market year, and 1.8 million metric tons of that is used for starch production (USDA GAIN, 2017c). Cornstarch production is concentrated in Andhra Pradesh, Karnataka, Gujarat, and Uttarakhand, as highlighted in Figure 13.

Figure 13. Main Cornstarch-Producing States

Wastewater Treatment

Cornstarch processing begins with cleaning and steeping, a controlled fermentation process where the corn is soaked in hot water. Kernels are then separated and dried, and oil is extracted from the corn and refined. Significant quantities of liquid and solid wastes are produced in the processing of cornstarch; and the major sources of liquid waste include steeping, separation, and fiber drying. For every metric ton of corn processed, an estimated 8.3 m^3 of wastewater is generated (GMI, 2011). Table 10 presents typical characteristics of cornstarch processing wastewater. Based on information collected for the previous India resource assessment, 14 percent of cornstarch processing wastewater in India is treated in open lagoons.

Table 10. Characteristics of Wastewater from Cornstarch Plants

Characteristic	Typical Range
pH (s.u.)	4–5
BOD (mg/L)	4,000–12,650
COD (mg/L)	10,000–20,000
TSS (mg/L)	5,600–11,000
TDS (mg/L)	4,000–6,000

BOD = biochemical oxygen demand, TDS = total dissolved solids,
TSS = total suspended solids.
Source: GMI, 2011.

Biogas Production Potential

For this assessment, GMI assumed that the 14 percent of cornstarch processing wastewater managed in open lagoons could be managed using AD systems, based on expert judgement. Table 11 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 11. Biogas Production and Direct Methane Emission Reduction Potential for Cornstarch Production in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	13
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	5
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	126
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	23

3.9 Tapioca Production

Sector Description

India is one of the world's major producers of cassava, an important root crop and a source of tapioca starch. While cassava is cultivated in 13 states in India, the key production areas are concentrated primarily in Tamil Nadu, but some production also occurs in the southern Indian states of Kerala and Andhra Pradesh (GMI, 2011). Figure 14 presents a map of the main tapioca-producing states, shown in dark blue.

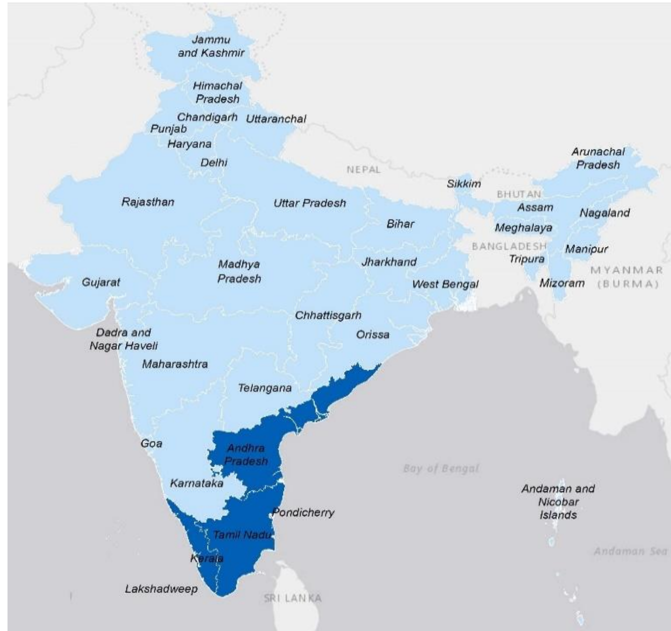


Figure 14. Main Tapioca-Producing States

Wastewater Treatment

Tapioca processing begins with washing and peeling. The tubers are then rasped, screened to separate pulp, dewatered, dried, and then pulverized and packaged for sale. Depending on the stage of the manufacturing process, wastewater characteristics will differ. Table 12 shows typical characteristics of combined tapioca processing wastewater.

Table 12. Characteristics of Wastewater from Tapioca Plants

Characteristic	Typical Range
pH (s.u.)	4.5–5.6
BOD (mg/L)	4,600–5,200
COD (mg/L)	5,631–6,409
TSS (mg/L)	565–640
TDS (mg/L)	3,435–3,660

Source: GMI, 2011.

Many tapioca plants are small and likely use open lagoons or do not treat their wastewater. Large plants are more likely to have anaerobic treatment for their waste. Based on information collected for the previous India resource assessment, GMI estimated that approximately 17 percent of tapioca processing wastewater is managed in open lagoons (GMI, 2011).

Biogas Production Potential

For this assessment, GMI assumed that the 17 percent of tapioca processing wastewater managed in open lagoons could be managed using AD systems based on expert judgement. Table 13 presents the biogas production and methane emission reduction potentials. Appendix A presents details of the calculations.

Table 13. Biogas Production and Direct Methane Reduction Potential for Tapioca Production in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	0.3
Direct Methane Reduction Potential (thousand metric tons CH_4/yr)	0.12
Direct Methane Reduction Potential (thousand metric tons CO_2e/yr)	2.9
Indirect Emission Reduction Potential (thousand metric tons CO2e/yr)	0.5

3.10 Crop Residues

Sector Description

India has 140 million hectares (TIFAC, 2018) of land under crop cultivation with a large variety of crops being grown. A substantial amount of crop residues is generated post-harvest. These residues are mainly used for animal feed, thatch for roofing, soil mulch and manure, and as a source of energy for rural households and industrial use. However, a large portion of the crop residues (referred here as surplus crop residue) is not utilized, and sometimes burned to clear fields for sowing the next crop. It is estimated that about 683 million tons of crop residue is produced annually from 11 major crops grown in India. The total annual surplus crop residues is estimated to be approximately 178 million tons. While burning the crop residues does not generate methane, it does have a substantial impact on air quality due to emissions of particulate matter. Crop burning in Punjab and Haryana impacts the air quality not just in the states where it is burned, but as far away as New Delhi, which is about 250 kilometers away. These crop residues are a potential feedstock for biogas projects.

Figure 15. Main Major Crop Producing States

The availability of major crops in India by state is provided in Table 14. The annual production of crop residues and surplus quantities of key crops is shown in Table 15. The States of Uttar Pradesh, Punjab, Maharashtra, Andhra Pradesh, Karnataka, Gujarat, Madhya Pradesh, Rajasthan, Haryana, West Bengal, and Tamil Nadu, highlighted in Figure 15, are the primary major crop (and crop residue) producing states.

Table 14. Availability of Major Crops of India by State

Crop Type	States
Rice	Uttar Pradesh, Punjab, West Bengal
Wheat	Uttar Pradesh, Punjab, Haryana
Bajra	Rajasthan, Gujarat, Maharashtra
Jowar	Maharashtra, Karnataka, Madhya Pradesh, Andhra Pradesh
Sugarcane	Uttar Pradesh, Maharashtra, Karnataka
Cotton	Maharashtra, Uttar Pradesh, Andhra Pradesh
Groundnut	Gujarat, Tamil Nadu, Andhra Pradesh
Oilseeds	Madhya Pradesh, Rajasthan, Andhra Pradesh, Karnataka, Maharashtra

Table 15. Crop-Wide Total Dry and Surplus Biomass

Methane Potentials	Dry Biomass (million tons)	Surplus Biomass (million tons)
Rice	225.5	43.9
Wheat	145.5	25.1
Maize	27.9	6.0
Sugarcane	119.2	41.6
Gram	26.5	8.7
Tur	9.2	1.8
Soybean	27.8	10.0
Rapeseed and Mustard	17.1	5.2
Cotton	66.6	29.7
Groundnut	12.9	3.9
Castor	4.6	3.0
All Crops	**682.6**	**178.7**

Note: Dry biomass refers to moisture-free content; totals do not sum due to rounding.

As shown in Figure 16, the States of Uttar Pradesh, Punjab, Maharashtra, Andhra Pradesh, Gujarat, Madhya Pradesh, Haryana, Telangana, Tamil Nadu, and Karnataka contribute about 87 percent of total surplus crop residue production in the country.

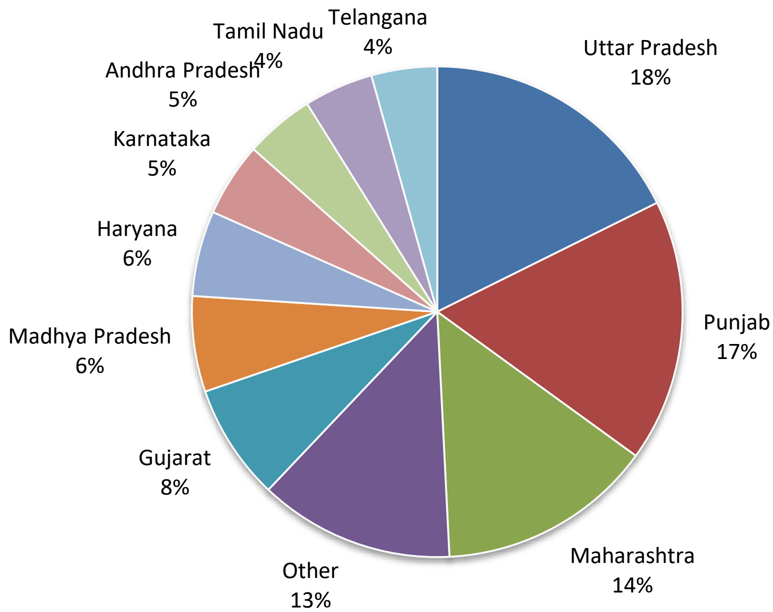


Figure 16. Major Crop Residue-Producing States by Percent of Surplus Production

Biogas Production Potential

For the assessment, GMI assumed that 25 percent of total surplus crop residues could be treated using AD, based on expert judgment. Table 16 presents the biogas production potential for crop residues. Methane emission reduction potential was not calculated since the burning of crop residues does not produce methane and GMI lacked data on how the remainder of the surplus crops are disposed of.

Table 16. Biogas Production and Direct Methane Production Potential for Crop Residues in India

Potentials	Value
Biogas Production Potential (million m^3/yr)	29,938

3.11 References

APEDA. 2015. Fresh Fruits and Vegetables. Agricultural and Processed Food Products Export Development Authority. Available: *http://apeda.gov.in/apedawebsite/six_head_product/FFV.htm. Accessed 5/29/2019.*

DAHDF. 2017. Annual Report 2016–2017. Department of Animal Husbandry, Dairying and Fisheries India. Available: *http://www.dahd.nic.in/reports/annual-report-2016-17*. Accessed 5/29/2019.

ENVIS Centre. Undated. Cleaner Production Opportunities in Distillery Sector. Gujarat Cleaner Production Centre. Available: *http://www.gcpcenvis.nic.in/Experts/Distillery%20Sector.pdf.* Accessed 5/29/2019.

FAO. 2018. Emissions by Sector. Food and Agriculture Organization of the United Nations. Available: http://www.fao.org/faostat/en/#data/EM. Accessed 5/28/2019.

GMI. 2011. Resource Assessment for Livestock and Agro-Industrial Wastes – India. Prepared for the Global Methane Initiative by Eastern Research Group, Inc.; TetraTech Consulting Group; and Federation of Indian Chambers of Commerce and Industry. January. Available: https://www.globalmethane.org/documents/ag_india_res_assessment.pdf. Accessed 5/28/2019.

Government of India. Undated. Annual Report 2017-18. Department of Animal Husbandry, Dairying & Fisheries, Ministry of Agriculture & Farmers Welfare. Available: *http://dadf.gov.in/sites/default/filess/annual_report_17-18.pdf*. Accessed 5/28/2019.

Government of India. 2014. 19th Livestock Census-2012. All India Report. Ministry of Agriculture, Department of Animal Husbandry, Dairying and Fisheries. Krishi Bhawan, New Delhi. June 17. Available: *http://dahd.nic.in/sites/default/filess/Livestock%20%205_0.pdf*. Accessed 5/28/2019.

Government of India. 2018. Horticultural Statistics at a Glance. Horticulture Statistics Division; Department of Agriculture, Cooperation & Farmers Welfare; Ministry of Agriculture & Farmers Welfare. November 27. Available: *http://agricoop.nic.in/sites/default/files/Horticulture%20Statistics%20at%20a%20Glance-2018.pdf*. Accessed 8/26/2019.

Mehrotra, R. and S.K. Mazumdar. 2016 Study on characterisation of Indian dairy wastewater. *International Journal of Engineering Applied Sciences and Technology* 1(11):77–88. Available: *http://www.ijeast.com/papers/77-88,Tesma111,IJEAST.pdf*. Accessed 5/28/2019.

National Dairy Development Board. 2017. Milk Production in India. Available: *https://www.nddb.coop/information/stats/milkprodindia*. Accessed 5/28/2019.

Srinivas, N.N. 2013. Poultry Droppings Can Generate Enough Gas to Run a Farm. Available: *https://economictimes.indiatimes.com/poultry-droppings-can-generate-enough-gas-to-run-a-farm/articleshow/19007572.cms.* Accessed 5/28/2019.

TIFAC. 2018. Estimation of Surplus Crop Residues in India for Biofuel Production. Joint Report of TIFAC & IARI. Technology Information, Forecasting & Assessment Council, New Delhi. October.

USDA GAIN. 2017a. Global Agricultural Information Network. India Biofuels Annual. Gain Report Number: IN7075. Available: *https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf*. Accessed 5/30/2019.

USDA GAIN. 2017b. Global Agricultural Information Network. India: Food Processing Ingredients. Gain Report Number: IN7150. Available: *https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Food%20Processing%20Ingredients_New%20Delhi_India_1-3-2018.pdf*. Accessed 5/30/2019.

USDA GAIN. 2017c. Global Agricultural Information Network. India Grain and Feed Annual. Gain Report Number: IN7031. Available: *https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_New%20Delhi_India_2-23-2017.pdf*. Accessed 5/30/2019.

VSI. 2018. Sugar Statistics – India. Vasantdada Sugar Institute. Available: *https://www.vsisugar.com/india/statistics/world_indiasugar.htm#.* Accessed 5/28/2019.

4. Technology Options

This section of the market opportunities assessment identifies current anaerobic digester technologies used in India. It summarizes key attributes of anaerobic digesters and identifies small-scale digester technologies used at a household or farm level, followed by medium- and large-scale digester technologies used on a commercial scale. It helps inform project developers and policymakers about the process, types of feedstock, and the scale at which each of these technologies is currently being implemented. Other AD technologies are available and in use in other countries, but are not currently appropriate for use in India. This section helps technology providers and project developers understand the technology landscape in India so they can consider adapting these alternative technologies to the Indian context.

A variety of anaerobic digestion (AD) technologies are in use in India. Technology designs vary, based on a number of attributes, including feedstock solids content, process stages, operation mode, and operation temperature, as shown in Table 17 and described below. Understanding these different attributes can help project implementers choose the right technology type to meet their needs.

Table 17. Attributes of AD Systems

Feedstock Solids Content	Process Stages	Operation Mode	Operation Temperature
▪ Wet ▪ Dry	▪ Single ▪ Multiple	▪ Batch ▪ Semi-continuous ▪ Continuous	▪ Thermophilic ▪ Mesophilic

- *Feedstock solids content:* AD systems are classified as high solids (“dry”) and low solids (“wet”) technologies based on the feedstock they process. Dry feedstock typically refers to a waste product with more than 15 percent solids content. Dry AD systems process materials that can be stacked and require little or no preprocessing of materials. These systems usually take feedstock from commingled yard and food waste. Other than removing contamination and properly mixing the material, no additional preprocessing is needed. Feedstock for wet AD systems must be preprocessed (e.g., have liquid added) to create a pumpable slurry for easy movement through the system. These systems usually process sewage sludge, manure, food processing industry wastewater, and clean food waste that is shredded and pre-processed to a slurry stage.
- *Process stages:* AD systems are single- or multi-stage systems based on the number of digester tanks in the series where the reactions take place. Two-stage systems are common, but some configurations include more tanks.
- *Operation mode:* AD systems are classified as batch, semi-continuous, or continuous based on how the feedstock material is introduced into the digester.
  - In batch systems, the digester is filled to its capacity with no mixing or additional feedstock until the processing time is completed. Feedstock is left in the reactor for the system’s designed retention time. These are the most robust AD systems with the highest tolerance for contamination and no significant feedstock preprocessing. Batch processing is used both in AD systems that process low-solid content feedstock such as manure and sludge and high-solid content feedstock such as the organic fraction of the municipal solid waste (MSW; usually a mix of food and yard waste).
  - In semi-continuous systems, a certain amount of feedstock is introduced into the reactor on a periodic basis (e.g., daily), while the same amount of digestate is removed from the effluent end of the digester. These AD systems may be used both to process low-solid content waste such as manure and high-solid content materials such as food and yard waste.
  - Continuous reactors are systems where the inflow of feedstock and the outflow of digestate is continuous. The flow rates are adjusted to allow for the necessary retention time for optimal rate of feedstock digestion. All continuous reactors need pumpable low-solid content feedstock with less than 20 percent total solid content. The feedstock needs to be in a homogeneous slurry form that is free from contamination so that it does not cause mechanical problems. These complex systems

require highly skilled operators and carefully chosen and prepared feedstock. Continuous reactors are suitable for wastewater treatment plant sludge, wastewater from the food processing industry, and diluted manure.

- *Operation temperature:* AD systems can be mesophilic or thermophilic based on operating temperatures. Mesophilic systems operate between 68 and 113 degrees F (20–45 degrees C) and thermophilic systems operate between 113 and 140 degrees F (45–60 degrees C). Mesophilic digestion is typically more stable and does not require heating, although gas yields are lower as the temperature decreases. Thermophilic digestion generally allows for reduced retention times, higher gas yields, and higher loading rates.

Understanding feedstock solids content, operation mode, processes stages, and process temperature is key to selecting the correct digester to use as different processers will be appropriate for different biogas projects. Using a digester that is suited to a project allows a user to more effectively and efficiently process waste and produce optimal quantities of biogas.

4.1 Small-Scale AD Technologies

Small-scale AD systems described here have a capacity of 130 m^3 in digester volume, or up to 7,000 m^3 of material processed per year. The main feedstocks typically consist of animal manure, human waste, crop waste, and/or food waste. These systems are often decentralized and serve a single farm or a household, and are usually privately owned by a household or farmer. The most commonly used simple and low-technology small-scale AD systems include fixed dome reactors, floating drum reactors, and bag digesters. Continuously mixed systems (described in Section 1.2.1 on medium and large AD systems) have been designed on a small-scale and used.

Fixed Dome Digesters

Fixed dome digesters (shown in Figure 17 and Figure 18) may be constructed of either concrete, bricks and mortar, or a combination of both. They are the most commonly used digesters for household biogas plants in India. It is estimated that around 80 percent of the 5 million digesters in India are fixed domes. These digesters are shaped like an igloo and built underground. Waste is fed into the digester through an inlet, often with a mixing pit located at the inlet. The waste decomposes in the body of the digester and the produced gas is collected at the top of the digester. The digestate slurry is displaced into a tank by the pressure of the produced gas.

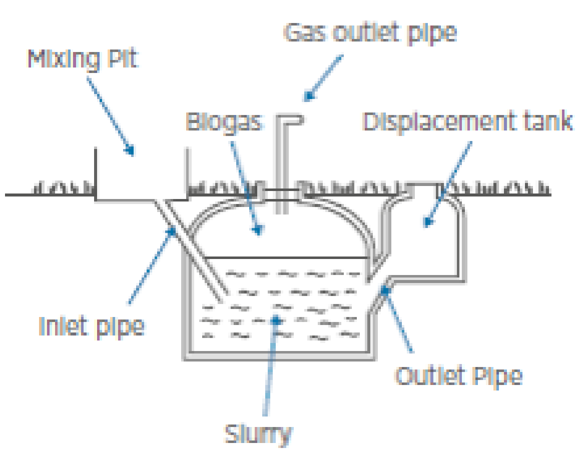


Figure 17. Fixed Dome Digester Diagram

Source: IRENA, 2017.

Figure 18. Fixed Dome Digester During Construction

Source: Mantopi Lebofa, 2006.

Deenbandhu digesters are a common type of fixed dome digesters in India. Deenbandhu digesters have a slightly different shape than other fixed dome digesters, as shown in Figure 19 and Figure 20. They are popular in India due to their ease of construction, low cost, and small footprint.

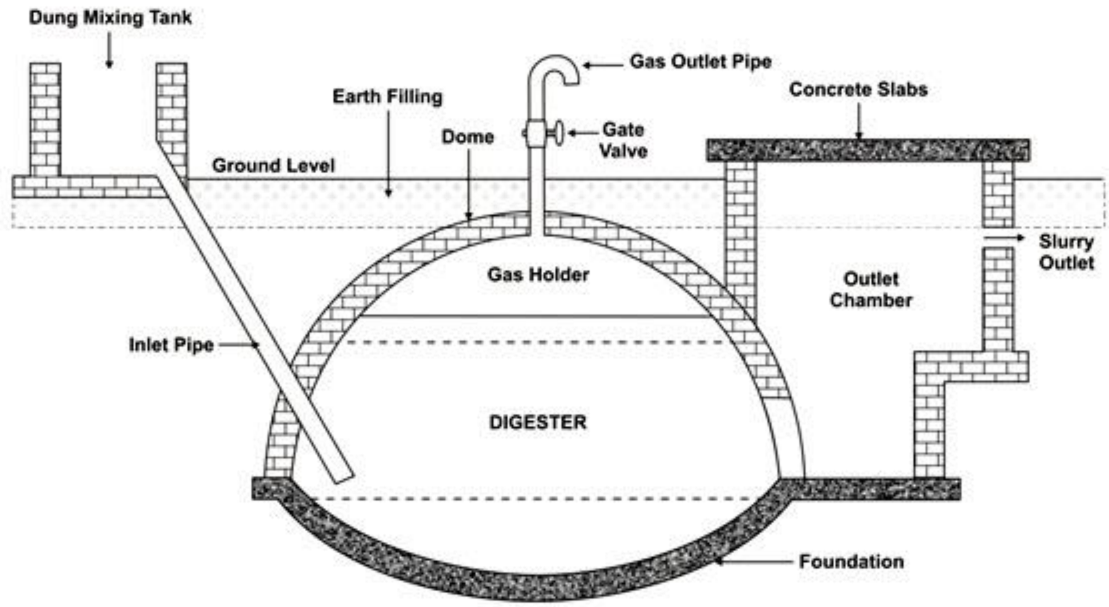


Figure 19. Deenbandhu Digester Diagram

Source: Singh, 2014.

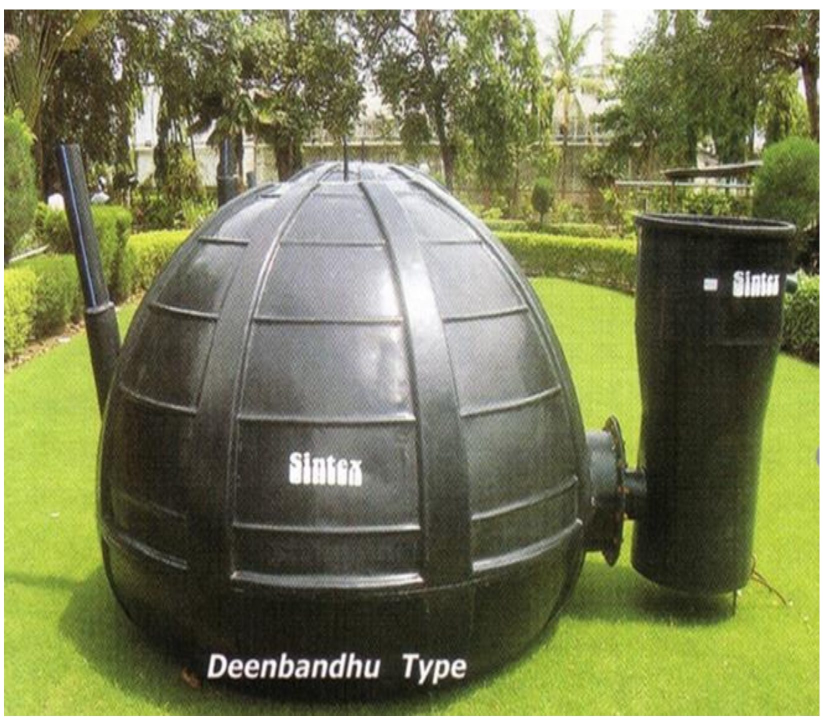


Figure 20. Deenbandhu Digester

Source: Sintex

Floating Drum Digester

The floating drum system (shown in Figure 21 and Figure 22) was originally developed in India by the Khadi and Village Industries Commission (KVIC), and consists of an underground reactor in brick or concrete and a stainless steel gas holder that floats on the top (the floating drum) along a central guide. The metal floating dome is used as gas holder, which is usually designed to store only a portion of the daily gas production as the produced gas is consumed throughout the day.

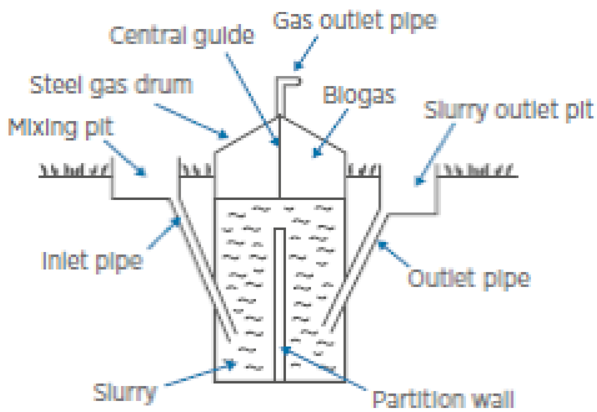


Figure 21. Diagram of a Floating Drum System

Source: IRENA, 2017

Figure 22. Floating Drum Digester

Source: McKay Savage, 2008

Floating drum systems have a robust design that are easy to construct from locally available materials. The digester can be constructed onsite and has a very long lifetime; but the stainless steel drum has to be fabricated at a specialized facility, and requires regular maintenance as it is subject to corrosion. The challenges associated with these systems are their higher costs and maintenance requirements when compared to a fixed dome system.

The National Biogas Program has promoted both the fixed dome and floating drum digesters to meet cooking fuel requirements of individual homes since 1982, and over 4 million household plants have been built in India.

4.2 Medium/Large-Scale AD Technologies

Medium and large-scale AD systems have a capacity larger than 130 m^3 in digester volume, or process more than 7,000 m^3 of material per year. Medium and large AD systems use a variety of feedstocks, including manure; sludge from wastewater treatment plants; organic fraction of MSW; food processing waste; fats, oils, and greases; and combinations of any of the above. Facilities of this size are considered commercial scale and may be centralized or decentralized.

Commercial-scale AD systems have been successfully implemented worldwide for more than a century. The largest number of commercial AD systems are in Europe, with 17,662 installations operating across Europe in 2016 (European Biogas Association, 2017). The combined number of AD systems generating biogas in the United States was around 1,500 in 2015, including wastewater treatment plants, farm-scale systems, and food waste systems (American Biogas Council, 2018). In India, over 450 biogas plants with a capacity of over 750 MWeq have been built for the recovery of biogas from wastes and effluents generated by various industry segments including distilleries, starch mills, and the food processing industry. In addition, many biogas plants of medium to large capacities have also been installed for producing biogas from cattle manure in rural areas of India. Medium-scale projects (around 100 m^3 to 500 m^3 biogas per day capacity plants) may also be based on the fixed drum and floating gas holder type digesters described in the previous subsection.

Completely Mixed Digester

Completely mixed digesters (shown in Figure 23 and Figure 24) are vertical cylindrical tanks made of concrete or steel and covered with an impermeable gas-collecting cover. Also known as Continuously Stirred Tank Reactors (CSTRs), these systems are the most popular digester option for large-scale applications. They keep heterogeneous feedstocks in a homogeneous form, and also improve the contact of the feedstock (heterogeneous and liquid effluents) with micro-organisms to increase digester efficiencies. Distillery effluents, poultry droppings, cattle manure, agro residues, and food processing industry wastes and residues are some of the feedstocks for which CSTRs are being deployed at large capacities.

Usually built above ground, they can be operated as mesophilic or thermophilic reactors. Processed material is continuously stirred by motor, pump, or recirculation of the produced biogas. Completely mixed digesters work best with feedstock such as manure diluted with water (e.g., milking center wastewater), preprocessed and diluted food waste, or food waste processing wastewater. Feedstock should be in slurry form and free of inorganic contaminants. These systems can process all types of feedstock (including codigestion of different feedstock), and high conversion efficiencies can be obtained. Depending on the operation temperature, the retention time can be as low as 15 days and these systems can operate in any climate as heating the digester content is more economically feasible due to high conversion efficiencies.

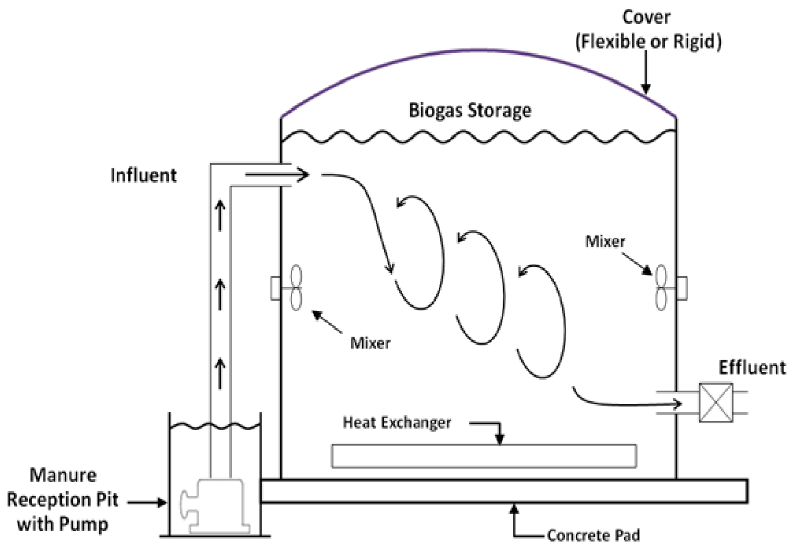


Figure 23. Diagram of Completely Mixed Digester

Figure 24. Completely Mixed Digester

Covered Lagoon

Covered lagoons are simple, low-technology, in-ground systems. The bottom of the reactor is lined and the lagoon is covered with an impermeable gas-collecting cover. The contents are typically not mixed and are usually connected to an effluent cell that is aerobic for collection of the processed material. Covered lagoons work best with manure handled via flush or pit recharge collection systems in warmer climates as covered lagoons are not typically heated. The feedstock these systems can handle has a low solid content (0.5 to 3.0 percent) and have relatively long retention times of 40 to 60 days. While costs will be lower, digestion efficiencies do not match those obtained in other digester systems. Figure 25 presents a diagram of a typical covered lagoon.

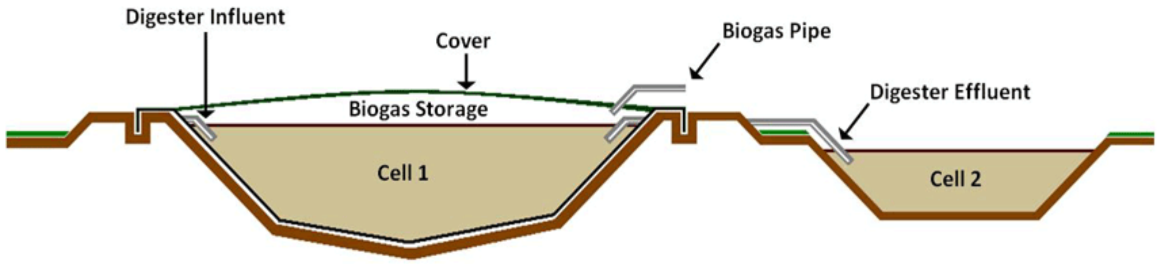


Figure 25. Diagram of a Covered Lagoon

Covered lagoon systems have been used quite extensively in hundreds of wastewater treatment facilities for cassava starch manufacturing in India.

Figure 26. Covered Lagoon

Source: USDA, 2012

Up-Flow Anaerobic Sludge Blanket (UASB)/Induced Blanket Reactor (IBR)

UASB/IBR (shown in Figure 27) is vertical cylindrical tank where the influent is added continuously from the bottom of the reactor and flows upward. The reactor contains a suspended sludge blanket comprised of microbial granules (1–3 mm in diameter). Microbial granules are small collections of microorganisms that are responsible for the biochemical reactions of the AD process (organic degradation and biogas production) and, due to their weight, cannot be washed out of the system with the upflow of the effluent (SSWM, 2018). Produced biogas rises to the top of the cylinder with the clarified effluent, and influent flow keeps the bacteria suspended in the reactor.

These systems are best suited for consistent, homogenous waste streams and are relatively simple to design and build. The challenging part of the system may be developing the granulated sludge. Chemicals known as flocculants need to be added to the system to help the formation of the granules, and the sludge blanket takes months to reach its processing capacity before the system can start operation.

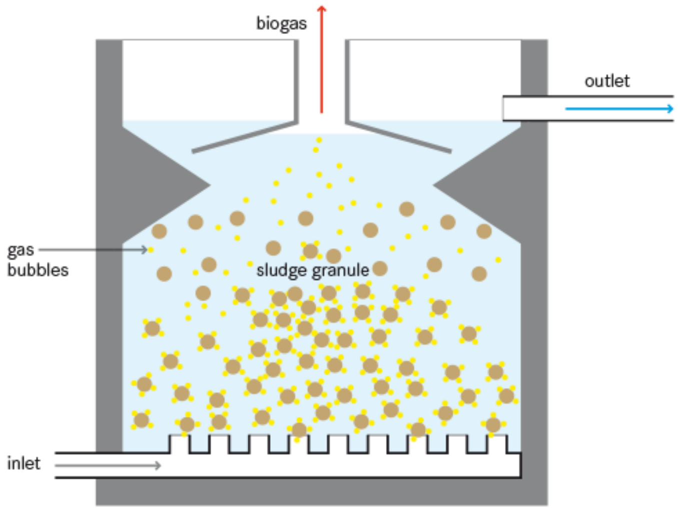


Figure 27. Diagram of a UASB Reactor

Source: SSWM, 2018

These systems are considered more advanced technology and require constant availability of water and electricity. UASB is a well-established process for centralized wastewater treatment plants and industrial wastewater treatment, and it has also been used to process water from brewery, distillery, food processing, and pulp and paper waste. The total solid content of the feedstock can be up to 12 percent. UASB systems allow for codigestion if all the feedstocks meet the criteria to be processed in this kind of system. UASBs are commonly used in India for lean feedstocks with low energy density or low volatile solids (VS)/chemical oxygen demand (COD)/biochemical oxygen demand (BOD). These include distillery effluents, starch industry wastes, sewage, paper mill effluents, slaughterhouse wastewater, and dairy industry wastewater.

Fixed Film/Attached Media Digester/Anaerobic Filters

Fixed film/attached media/anaerobic filters are vertical cylindrical tanks made of concrete or steel with an impermeable flexible cover on the top for the collection of biogas. In these reactors, microorganisms that facilitate the feedstock biodegradation and biogas generation are attached as a film to a medium, typically ceramics or plastics. The inflow of feedstock may be at either the top or bottom of the reactor in a downflow or upflow configuration, respectively. As the feedstock flows through the digester, it is processed by the microorganisms on the film. These systems are best suited for a very low total solid content in the feedstock (1 to 5 percent) and therefore have the greatest application in processing wastewaters, and are extensively used in India. Figure 28 shows an upflow configuration with solids being separated and the manure liquid fed into the digester.

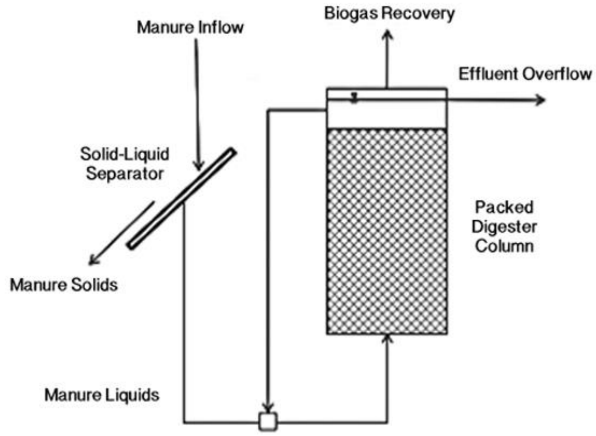


Figure 28. Example Fixed Film Digester

Source: eXtension Foundation, 2019

Plug Flow Digester

Plug flow digesters are constructed with concrete or steel, are typically long and narrow, with an impermeable gas-collecting cover. Contents move through the digester as new material is added. Modified plug-flow systems use shafts for mixing the substrate in the direction perpendicular to the direction of flow and moving the material through the reactor. These systems can handle manure with animal bedding, food waste, and yard waste. When processing food waste and yard waste, they need to be preprocessed to homogenize the material. Figure 29 presents a diagram of a typical plug flow digester.

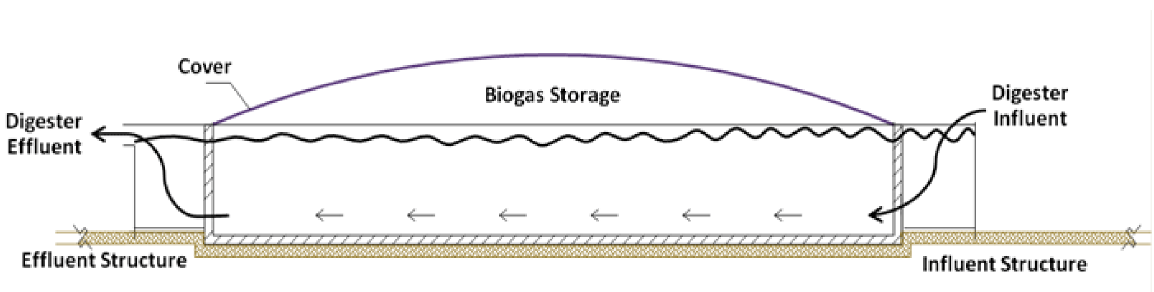


Figure 29. Diagram of a Plug Flow Digester

These systems are considered simple and robust to a certain extent, as the reactors can tolerate contamination and no significant preprocessing of the material is required. These systems have no limitations with reference to optimal climate conditions, have a retention time of more than 15 days, and the material processed can have a solids content of up to 40 percent.

"Garage"-Style Dry AD Systems

"Garage"-style dry AD systems (shown in Figure 30 and Figure 31) are simple by design and very robust. These systems are long tunnels with perforated floors, and flexible impermeable covers for gas collection. Material is processed in batches; once the system is filled, the doors are closed and the material is left in the reactor for an average of 21 days. This system can process material with a solid content in excess of 50 percent without additional moisture needed.

Dry AD systems of this kind gained popularity in Europe when the disposal of non-processed organics was banned. These reactors are very flexible regarding the level of contamination in the feedstock, allowing for digestion of organic waste from MSW, including mixed food and green waste.

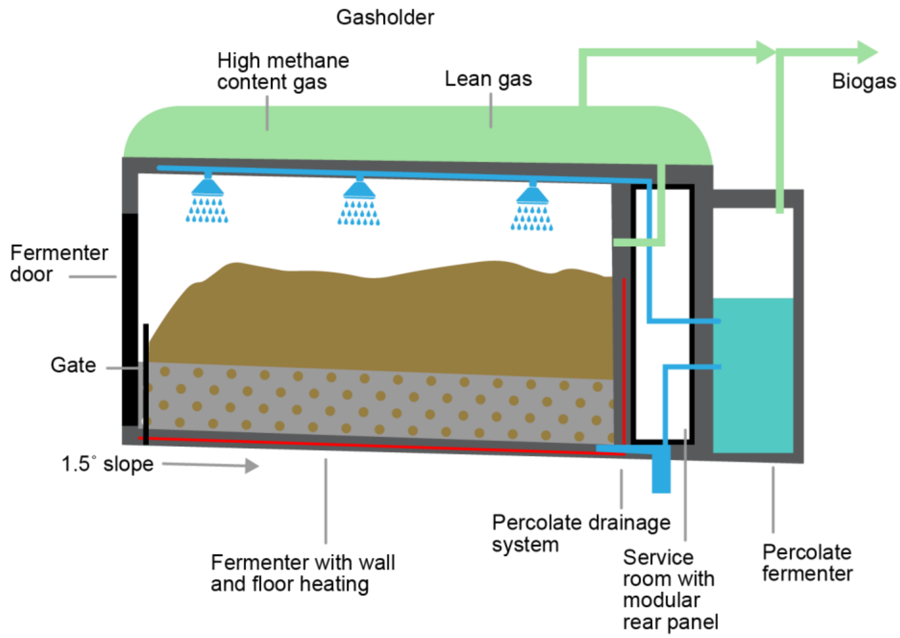


Figure 30. Diagram of a Dry AD System

Figure 31. Dry AD System

These systems typically include an above-ground digester where the feedstock is added, airtight doors, and an underground percolator chamber. Leachate produced during decomposition of the material in the digester is collected in the percolator chamber and spayed over the material in the main digester. These systems produce biogas from the material in the main reactor and the leachate in the percolator chamber. Recirculation of the leachate allows for these systems to run as thermophilic systems, which increases the biogas production and the rate of degradation. While the capital and operating costs of these digesters are expected to be lower, these types of systems are also generally associated with lower digestion efficiencies.

A large-scale (4 MW) facility using this technology is currently processing segregated municipal solid waste in Solapur, Maharashtra. This is the only pilot facility of this type in India and is yet to be replicated.

Anaerobic Sequencing Batch Reactors (ASBRs)

ASBRs are typically cylindrical, made of concrete, above-ground, with an impermeable roof below which gas is collected. They are used to process wastewater or treat dilute wastes (e.g., manure handled as a slurry). Feedstock is added and removed from the reactor in batches.

These reactors include four processing phases in sequence as follows:

1. Filling phase,
2. Reaction phase
3. Settling phase
4. Decanting phase.

These reactors can process material with 2.5 to 8 percent solids in a relatively short retention time (up to 5 days). ASBR systems work in all climates and are suitable for codigestion of different organic feedstocks. These digesters are not typically used in India due to higher costs and lower efficiencies.

4.3 References

American Biogas Council. 2018. Biogas Projects. Available: *https://americanbiogascouncil.org/resources/biogas-projects/*.

European Biogas Association. 2017. EBA Statistical Report 2017. European Biogas Association. Available: *http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/*. Accessed 5/29/2019.

eXtension Foundation. 2019. Farm Energy. Types of Anaerobic Digesters. Available: *https://farm-energy.extension.org/types-of-anaerobic-digesters/*. Accessed 5/29/2019.

IRENA. 2017. Biogas for Domestic Cooking: Technology Brief. International Renewable Energy Agency, Abu Dhabi Brief, International Renewable Energy Agency, Abu Dhabi.

Singh, S.K. 2014. Waste and By-Product Utilization. Lesson 6. Biogas. Available: *http://ecoursesonline.iasri.res.in/mod/page/view.php?id=1430*. Accessed 5/29/2019.

SSWM. 2018. Upflow Anaerobic Sludge Blanker Reactor (UASB). Sustainable Sanitation and Water Management. Available: https://www.sswm.info/water-nutrient-cycle/wastewater-treatment/hardwares/semi-centralised-wastewater-treatments/upflow-anaerobic-sludge-blanket-reactor-%28uasb%29. Accessed 5/29/2019.

5. Business Models and Case Studies

India has the world's largest population of dairy animals, the majority of which are located at small-scale dairy farms. While the potential for biogas project development in India is substantial due to the availability of feedstock, projects can always fail due to a number of operational and financial challenges.

Historically, agricultural biogas projects in India have been owner-operated and comprised of household-scale systems that are primarily located in rural areas. These small systems have capacities ranging from 1 to 1,000 m^3 of biogas per day and are generally managed by individual households to generate cooking fuel. The Government of India announced the Sustainable Alternative Toward Affordable Transportation (SATAT) Initiative in October 2018 to reduce India's dependence on oil and gas imports by producing bio-compressed natural gas (bio-CNG) using agricultural residues, cattle dung, sugarcane press mud, municipal solid waste (MSW), and sewage treatment plant waste. It is anticipated that 5,000 projects will be developed in 5 years. Due to universal challenges facing digester development such as high capital costs, variable energy prices, and infrastructure hurdles, there is an increased focus on opportunities to share project risk and reward, and diversify project revenue sources.

This section of the market opportunities assessment discusses business models, from India and those in use world-wide, including key aspects of successful anaerobic digestion (AD) systems, potential owner and operator models, and diversification of revenue generation; and provides case studies to highlight successful business models.

5.1 Aspects of Successful AD Systems

Many factors need consideration to implement and operate an AD/biogas system. The following list briefly introduces the essentials for a successful farm-based digester project. The AgSTAR Project Development Handbook (EPA, 2004) developed for the United States domestic biogas projects identifies 10 keys to digester success, which are summarized in Table 18.

Table 18. Foundations for a Successful AD/Biogas System

Action	Desired Outcome
Plan for Success	Identify and define project goals. Specify the parameters to address and how to meet them.
Recruit and Secure an Experienced Team	Work with an experienced team to initiate and successfully implement your project.
Secure a Continuous and Quality Feedstock Supply	Identify all suitable feedstocks. Test them for biomethane potential and anaerobic toxicity.
Use Most Appropriate Technology	No AD technology can be used for all situations or feedstocks. The technology plan must match the feedstock type and amounts used.
Analyze Options for Most Favorable Biogas Use	Consider market availability, capital and operating costs, and potential revenue to determine the best use for biogas.
Assess Digestate Use	Determine the need for onsite use and consider external markets for products such as bedding, fertilizer, or compost.
Develop Off-Take Agreements	Establish off-take agreements for energy, digestate, and co-products, including the price, amount, and specifications for delivered products.
Evaluate Added Benefits	Consider climate, health, soil, sustainable food supply, community relations, and odor control.
Use a Sustainable Business Model	Not only should the project be cost-effective, it must meet your financial goals.
Plan for Operation and Maintenance	Good process and maintenance practices are key for optimal and uninterrupted operation.

5.2 Owner and Operator Models

There are a number of business models with respect to who owns and operates the AD system. Successful business models:

- Involve partners along the value chain, such as co-operatives, customers, suppliers, and processors
- Draw on strengths such as marketing, contracting, permitting, energy, design, or operations
- Search for common goals such as financial, public relations, or market expansion
- Evaluate third-party investment, ownership, and operation
- Look to traditional cooperative models for use with manure solids, nutrients, energy, or fuel.

General types of business model ownership structures may include:

- **Farmer owned and operated.** A farmer typically owns and operates a digester onsite and uses manure from the farm, at a minimum, as feedstock. In some cases, the farmer may accept manure or other organics from offsite, generally for a tipping fee.
- **Third-party owned and operated.** A site owner may receive a rental fee or a share of the project's net income, but the third party owns, operates, and invests in the digester. The third party may be a venture capitalist or an investment group specializing in green energy projects. The third party may also manage the feedstock.
- **Third-party operated.** A third party, who does not own the digester, operates the digester, manages the feedstock, and manages other aspects of the energy and effluent sale. The digester and feedstock can be owned by a single entity or many entities.
- **Hub and spoke.** This business model can take two general forms: centralized digester or centralized processing, either of which could be owned by a municipality or third party. It could also be part of a cooperative, which relies on a voluntary partnership of individuals that jointly own and democratically control the project.
    - **Centralized digester.** Feedstocks from multiple locations are collected and transported to a centralized anaerobic digester. It can be advantageous for communities to build one digester and distribute the biogas and digestate generated.
    - **Centralized processing.** Digesters at multiple locations send the biogas and/or digestate to a centralized processing facility. Biogas and digestate processing equipment can be expensive and a centralized processing facility could be a cost-sharing opportunity, lowering the financial burden for each entity.

5.3 Diversification of Project Revenue Sources

Business models, irrespective of ownership and operators, may also incorporate the following aspects to help improve project revenue and ensure economic feasibility of the project:

- **Codigestion.** As with sales of coproducts and biogas, a business model that includes codigestion of different feedstocks can offset costs and generate revenue for a facility with an anaerobic digester due to tipping fees and increased biogas production. Codigesting waste can help to diversify and financially stabilize a facility's business. For example, a digester built to process agricultural waste could also process organic MSW and the digester operator/owner could charge a tipping fee.
- **Value-added products.** Some owners/operators may develop innovative products in order to make their AD systems more economically feasible. For example, digestate can be composted and sold as a fertilizer. An emerging trend is to upgrade produced biogas to renewable natural gas (RNG), which can be used interchangeably with conventional natural gas.
- **Closed loop.** A biogas system can be a self-sustaining system when the feedstock generators, the biogas producers, and the energy and digestate users are all linked to use each other's products efficiently and economically (see Figure 32). For example, a dairy or community could provide cow dung or other organic waste to a biodigester, the electricity or biogas generated from the biodigester could be sold back to the dairy or the community. Similarly, biodigester could supply digestate to a farm as

fertilizer that could support the growth of fodder to the dairy, which would supply cow dung to the biodigester.

- **Cooperative/value chain inclusion.** The viability and success of projects can be improved if entities throughout the value chain invest in the digester and/or equipment, thus spreading the risks and rewards.

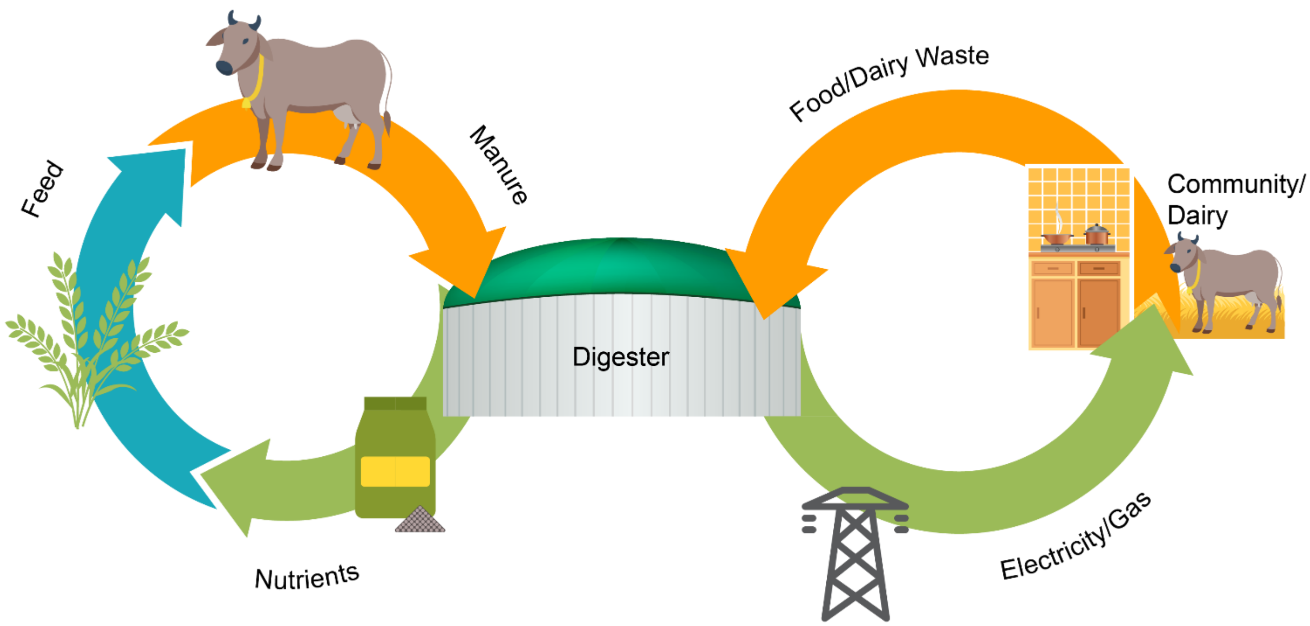


Figure 32. Closed Loop Biogas System

5.4 Case Studies

Case studies, summarized in Table 19, are presented in this section to illustrate different business models.

Table 19. Summary of Case Studies

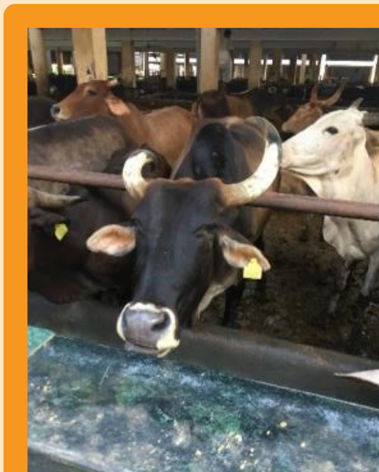
	Govind Goudham Gaushala	Haibowal Dairy Complex Project	Rohtak: Source Facility and Biocity
Biogas use	▪ Cooking fuel ▪ Electricity	▪ Electricity ▪ Bio-CNG ▪ Bio-CO_2	▪ Bio-CNG for cooking
Project benefits	▪ Environmentally friendly and sustainable waste disposal ▪ Income from fertilizer and savings on electricity ▪ Community independence ▪ Houses are cooler, light is reliable, and food can always be made	▪ Reduced risk of run-off and leaching nutrients ▪ Conversion of nutrients from organic to inorganic form ▪ Plant visibility nationally and internationally	▪ Income from fertilizer
Project start date	2014	September 2004	Unknown
Baseline system	Direct discharge	Direct discharge or manual collection for cow dung cake as fuel	Manual collection for cow dung cake as fuel
Digester type	Khadi and Village Industries Commission (KVIC) floating drum	Intermittently stirred tank reactors	Unknown
System designer	Unknown	Original biogas system: Entec Biopower Bio-CNG and bio-CO_2 expansion	Source facility
Digester inputs	Manure from 1,780 cattle	Manure from 80,000 dairy cattle	Manure from 2,000 cows
Biogas production potential	150 m^3 per tank	10,000 m^3/day	6,000 m^3/day
Generating capacity	40 kW	1 MW	Unknown
Project costs	44.5 lakh INR (71,000 USD) total cost, reduced to 14 lakh INR (22,000 USD) with subsidy from the Ministry of New and Renewable Energy (MNRE)	1,500 lakh INR (2.2 million USD) for demonstration project; 521 lakh INR (820,000 USD) for bio-CNG and bio-CO_2 expansion	N/A
Business Model Aspects	▪ Value-added products	▪ Centralized digester ▪ Value-added products ▪ Bio-CNG ▪ Considering codigestion	▪ Third-party operated ▪ Centralized digester ▪ Bio-CNG ▪ Value-added products ▪ Considering codigestion

Table 20. Summary of international Case Studies (continued)

	ARC Bio Fuel	Kern Dairy Biogas Cluster	Philippines Tube Digesters
Biogas Use	Bio-CNG (varies by end user)	▪ Electricity ▪ Renewable Natural Gas pipeline injection ▪ Bio-CNG for vehicle fuel	▪ Cooking fuel ▪ Electricity/lighting ▪ Vehicle fuel (on one example farm)
Project Benefits	Restore organic carbon content in soil through digestate fertilizer use	▪ Reduced risk of run-off and leaching nutrients ▪ Adds to the local economy	▪ Reduced odors ▪ Improved water quality ▪ Reduced cooking and electricity costs ▪ Fertilizer for farms
Project Start Date	January 2016	2013	July 2011
Baseline System	Direct discharge	Storage lagoons	Direct discharge
Digester Type	Continuously stirred tank reactor	Covered lagoons	Tube digester
System Designer/ Project Developer	CEID Consultants & Engineering Pvt Ltd.	4 creeks/California Biogas LLC (CalBio)	Environmental Fabrics, Inc. (demonstration system); Buklod-Unlad (subsequent systems)
Digester Inputs	Manure from cows and poultry	Manure from 100,000 cattle (approximate planned total)	Manure from pigs
Biogas production potential	5,000 m^3 per day	5 million diesel gallon equivalents (approximate planned total)	Varies by project
Generating capacity	1,847 kg per day	12 MW (approximate planned total)	Varies by project
Project costs	573.91 lakh INR (850,000 USD)	Unknown	Unknown
Business Model Aspects	▪ Centralized digester ▪ RNG ▪ Value-added products ▪ Third-party operated	▪ Centralized gas processing ▪ Codigestion ▪ Renewable Natural Gas	▪ Community AD cooperative for household-scale systems

5.4.1 - Govind Goudham Gaushala

In the Village of Hambran in the Ludhiana district of Punjab, a cattle shelter and neighboring school that once struggled with high energy costs and unreliable electrical availability are now generating their own power, thanks to AD. The small community of Govind Godham is home to 80 families and a cow shelter (gaushala) that cares for nearly 2,000 sick, injured, or retired cattle. Adjacent to the shelter is Ek Muskaan, a temple-run school that strives to eradicate poverty and slavery in the region. The biogas plant, installed in 2014, provides reliable electricity to keep the shelter machinery running smoothly and the lights on at the school, as well as cooking fuel for the shelter's kitchen. Savings from the electricity generation, in addition to income received from the sale of fertilizer, have allowed many improvements to be made to the shelter and school.



Govind Godham cow shelter

Project Costs and Revenues

The total cost of the plant, which was promoted by Punjab Energy Development Agency, was 4,450,000 INR (71,000 USD). Nearly 70 percent of that total cost was covered by the MNRE, which subsidizes biogas power. The remaining 1,400,000 INR (22,000 USD) was paid for through local fundraising efforts to collect donations. In 2015, the plant was fully operational.

Cart for transporting cooked meals to the community.

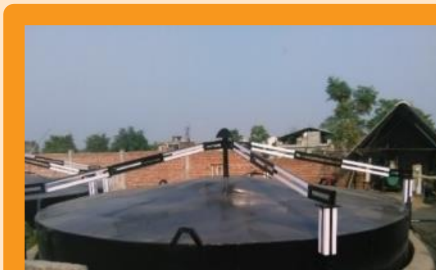
Ludhiana is an agricultural city, so the fertilizer produced from the plant is sold to generate additional income for the shelter, temple, and school. Each tanker load sold brings in about 500 INR (8 USD). Fertilizer is also used on farms at the shelter, which produce food and fodder for the cows to eat.

Cost savings from the self-generation of power in addition to the increase in funds resulting from fertilizer sales have provided significant benefits to the community. The Ek Muskaan school has expanded, with new classrooms and facilities for students. Many improvements have been made to the cow shelter, including the installation of fans to keep the animals comfortable during the summer and special accommodations for injured cattle. An onsite hospital for cattle and humans is now fully equipped with professional veterinarians and medicine. Children are happy because their houses are cooler, light is always available, food can be made at any time, and the shelter machinery is in good condition.

System Components and Operation

The Govind Godham biogas plant consists of the following elements:

- Mixing pit
- 3 KVIC floating drum digester tanks
- 50 kVA biogas engine
- Biogas stoves



One of three floating drum digesters

Shelter staff cart cattle manure via wheelbarrows from the stalls and deposit it into a mixing pit, where it is combined with water to reduce its viscosity. From the pit, the mixed slurry is sent through one of three channels, each leading to one of three digester tanks. Only one tank operates at a time, so valves to the non-operating tanks remain closed. Biogas produced in one tank is sent directly to the community kitchen, where food is prepared for students, shelter workers, and other community members and visitors. Gas from another tank is passed through a 40-kW generator, which produces enough electricity to run the fodder cutting machines used to make food for the cattle, as well as fans for the cows and fans and lighting at the school.

The floating drum model is the oldest digester type in India. It consists of an inverted steel gas storage drum, fitted over a deep well into which the manure slurry is piped The drum moves up and down around a guide pipe, depending on the volume of gas collected within the drum. Advantages of this model include a steady gas pressure (due to the drum movement) and the ability to judge gas volume based solely on the position of the drum.

One of the kitchen's biogas powered stoves

40-kW generator

5.4.2 – Haibowal Dairy Complex

Commissioned in 2004, the Haibowal Dairy Complex high-rate AD project demonstrates large-scale power generation from cattle manure in India. Located in Ludhiana, Punjab, the 1-MW project was the first of its kind and has proven the technical feasibility of developing such projects for energy recovery as well as producing large quantities of enriched organic fertilizer and reducing GHG emissions.


Haibowal Dairy digester tanks and biogas storage unit

Project Background

The Punjab Energy Development Agency (PEDA), in conjunction with India's Ministry of New and Renewable Energy under the United Nations Development Programme (UNDP), initiated this project to:

- Demonstrate the viability of large-scale energy recovery from cattle manure
- Reduce GHGs
- Improve water quality
- Help address the region's increasing energy needs.

Municipal Corporation, Ludhiana, allocated 2.4 acres of land for the project, and Entec Biopower (Austria) designed the system. Work on the project began in April 2002, and the project was successfully connected to the grid in September 2004. The Punjab State Electricity Board laid the transmission line and committed to a power purchase agreement at a rate of 3.49 INR/kWh (5 cents/kWh), which was the amount assigned for the project as the project was set up with financial support from MNRE and the Government of Punjab; this amount is expected to cover only operating expenses. The total capital cost for the demonstration project was about 150 million INR (2.3 million USD), which was covered by a grant from the Government of India and the State Government of Punjab.

After the demonstration project was successfully operating, PEDA contracted out the biogas plant operation and maintenance to several companies. From 2012 to 2016, the Dutch company DSM Biogas improved the facility's operational practices by providing regular training for support staff, servicing and repairing electrical and mechanical equipment to increase reliability, and streamlining feedstock supplies from the local dairies.

In 2015, to improve its commercial performance in light of reduced power prices, DSM Biogas established a state-of-the-art bio-CNG plant and a CO_2 recovery plant. The new installations cost about 60 million INR and opened a new revenue stream through the sale of bio-CNG and its byproduct CO_2.

Improving Water Quality, Reducing Emissions, and Harnessing Renewable Energy

Manure from approximately 80,000 cattle on adjoining dairies at the complex serves as the feedstock for two 5,000 m^3 tank reactors. This waste would otherwise be discharged into Buddha Nullah, a seasonal stream that passes through the highly populated Ludhiana district before draining into a tributary of the Indus River. The plant is estimated to prevent 1.7 billion liters of manure wash from being discharged annually. Furthermore, the freshwater requirement for mixing is reduced by about 1.6 billion liters each year through water recycling.


Biogas engine genset

The digesters produce 47 tonnes per day of fertilizer, which is sold by PEDA for 1,000 INR (15.62 USD) per tonne. This fertilizer has the potential to replace the harmful, urea-based fertilizers that would be applied to 800 acres of land.

The system reduces GHG emissions by an estimated 4,800 $MTCO_2e$ annually and generates approximately 6 million kWh/yr of clean, renewable electricity. The plant also produces bio-CNG, a fuel that may be sold as an alternative to fossil fuels.

System Components and Operation

The following elements comprise the high-rate bio-methanation plant at Haibowal Dairy Complex:

- Two intermittently stirred tank reactors
- Biogas storage unit
- Biogas engine genset
- Biogas upgrade system
- Storage unit for upgraded biogas
- Compressor
- Liquid CO_2 tank
- Flare.

Flexible storage unit for upgraded biogas

The plant accepts about 160 tons of cattle manure per day, and is exploring other potential feedstocks including spoiled cattle feed, poultry waste, and pressed mud (waste from sugarcane processing). The plant is designed for a daily feed of 230 tonnes (consisting of about 16% total solids) of cattle manure per day. Recycled water is added, and the manure slurry is stirred intermittently in the digester tanks based on the biogas-induced mixing arrangement. Generated biogas is stored in a 1,000-m^3 bell-and-shell-type storage balloon made of neoprene-coated nylon fabric. Waste heat recovered from the engine is directed back to the mesophilic digester tanks to keep them operating at 37°C. Separated solids from the digesters' effluent contain less than 70 percent moisture and are sold as organic fertilizer.

Bio-CNG compressor unit

Biogas Use

In addition to being the country's first large-scale, manure-based biogas power plant, this facility is also the country's first plant to separate biogas into methane and CO_2 gases for domestic or commercial use. The trial period for bio-CNG filling began in July 2017. The facility has the capacity to generate 4,000 kg of bio-CNG per day and can fill 40 10-kg cylinders at a time. The cylinders are sold to customers at 450 INR (7 USD) each.

Bio-CNG can be used in many applications as a substitute for imported CNG as well as liquefied petroleum gas (LPG). The purified CO_2 can be used in the beverage, textile, or the welding industry; or for other applications such as in dry ice and fire extinguishers.

5.4.3 – Source Facility and Biocity, Rohtak

Source Facility and BioCity are complementary companies founded by Abhishek Handa and Akshay Asija, entrepreneurial project developers based in India. The companies were established to address the operational challenges of biogas systems and meet the energy and fertilizer demands in India. Source Facility is a third-party operator of biodigester systems and manages the day-to-day operations of large-scale biodigesters. The company develops key relationships with local farmers and waste producers to source feedstocks, and manages the digester operations and production of high-quality biogas. BioCity markets and distributes the biogas and biofertilizer products to end users in rural and urban communities across India. It is an innovative business model that improves projects' economic, environmental, and social output through the entrepreneurs' involvement in all stages of biogas and biofertilizer production and use.

Source Facility

Source Facility works with owners of existing or planned biodigesters by:

1. Aggregating and supplying feedstock, including cow dung, sugar cane milling residue (press mud), and other agricultural residues
2. Analyzing feedstock chemistry to optimize biogas production
3. Providing an onsite technician to ensure proper operations
4. Building relationships with local farmers and waste production facilities to source feedstocks, and creating new jobs and income for rural communities.


Biodigester

Source Facility currently operates four biodigester facilities in India. Its facility in Rohtak, Haryana, has a design capacity of 80 tonnes/day. It processes manure from up to 2,000 cows from farms within 20 km of the project, and can produce up to 6,000 m^3 of biogas per day. The project can also codigest press mud from sugar cane mills and other agricultural residues.

BioCity

BioCity markets and distributes biogas and biofertilizer produced by the facilities operated by Source Facility. BioCity supports local communities by:

1. Providing cylinders of compressed biogas to local restaurants for cooking, manufacturers for production fuel, and others for vehicle fuel
2. Providing logistical support to transport the products to end users
3. Providing technical support to end users to ensure safe use of the gas
4. Meeting the fertilizer needs of rural and urban India.


Cylinders with compressed biogas

Source Facility and BioCity contribute to methane mitigation by capturing and using biogas from cow dung and agricultural residue. Additionally, because their projects offer an alternative use for crop residues that are typically burned in fields, they are helping to reduce black carbon emissions and protect local air quality.


Manure from digestate

5.4.4 – ARC Bio Fuel Private Limited

In the Barnala district of Punjab, India, ARC Bio Fuel Private Limited operates a bio-CNG and fertilizer plant that runs on manure. Incorporating India's first anaerobic digester with a double membrane cover, the plant was installed by CEID Consultants & Engineering Private Limited (CCEPL) and became operational in January 2016. It is a producer and supplier of bio-CNG and organic fertilizer.

Arc Bio Fuel CSTR

Plant Profile

The plant accepts 119 MT per day of cow and poultry manure from surrounding farms and produces over 1,800 kg of bio-CNG daily. With no pipelines available for distribution, the plant sells small canisters of CNG to end users such as commercial kitchens or industrial manufacturing facilities. Currently, Arc Bio Fuel has around eight customers.

The solid digestate from the plant's Continuously Stirred Tank Reactor (CSTR) anaerobic digester is packaged and sold as "Biovy Organic Manure." This product is composed of approximately 60 percent cow manure and 40 percent poultry manure. It is 1.5 to 2.0 percent nitrogen, 0.8 percent phosphorus, and 0.8 percent potassium (Arc Bio Fuel, Undated). The use of this organic fertilizer increases the organic carbon content of the soil.

MNRE, in collaboration with PEDA and Punjab National Bank, provided support for this project. MNRE and PEDA covered 20 percent of the project's capital costs.

System Components and Operation

ARC Bio Fuel's system consists of the following elements:

- Mixing pit
- CSTR
- Biogas storage bag
- Pressure swing adsorption system for biogas purification
- Bio-CNG cylinder cascades.

Cow and poultry waste are brought to the plant and placed in an intake pit, where it is mixed and pumped into a feeding pit. From the feeding pit, it is pumped into the plant's CSTR AD system. The digester is heated by an internal concentric-tube heat exchanger. Hot water is circulated through the heat exchanger by a central heating pump. Agitators inside the tank mix the substrate to distribute the nutrients in the biogas digester uniformly, to form a suspension of liquid and solid parts, to avoid sedimentation of particles, to ensure uniform heat distribution, to prevent foam formation, and to enable gas lift from the fermentation substrate at high dry matter contents.

Arc Bio Fuel Biovy Organic Manure

Source: Arc Bio Fuel, Undated.

Biogas is collected at the top of the tank and is pumped to a separate gas holder. The biogas flow is measured from the double membrane gas holder via low-level condensate traps. The gas holder is inflated by an air blower and pressure is maintained at a constant level.

The biogas produced by the plant's CSTR is purified using pressure swing adsorption. The purified gas is compressed and bottled into cylinders. One cascade of cylinders is able to hold around 150 kg of CNG. This bio-CNG is sold for cooking and heating uses.

The digestate is withdrawn from the base of the digester. The amount of digestate discharged and the time between each discharge is variable and can be adjusted by the operator.

Biogas purification system

Arc Bio Fuel bio-CNG cylinder cascade

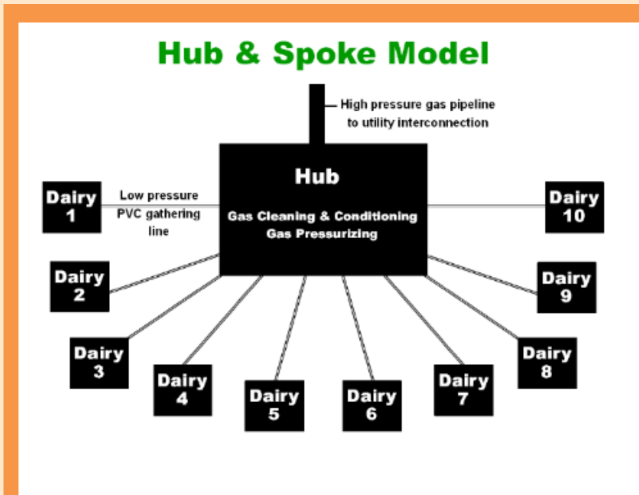
Bio-CNG being used for cooking

5.4.5 – Kern Dairy Biogas Cluster

In the United States, the State of California has 1.7 million dairy cows and 1,400 dairy farms. The state produces 20 percent of the United States' milk. Because of the concentration of farms in California and the incentives available for renewable energy projects, there is a good opportunity for AD project development. The Kern Dairy Biogas Cluster represents a business model that could translate to the Indian market.

Project Overview

California Biogas LLC (CalBio) was founded in 2006 to focus on dairy biogas in California. The group identified a cluster of 15 modern, large dairy farms in Kern County, California. CalBio is working to develop AD projects on these farms, which typically manage their manure in uncovered lagoons. Once complete, the project will be the state's first "hub-and-spoke" dairy digester cluster.



Planned Kern Dairy Cluster Project

As of August 2019, four systems are operating, including a covered lagoon system at the Old River Road Dairy, which is the largest dairy digester in California, accepting waste from over 15,000 dairy cows. It began operating in 2013 and includes a two-cell lagoon digester where it codigests manure and food waste. It currently uses a 2-MW generator to produce over 16,000 MWh of renewable electricity per year, which is exported to Pacific Gas and Electric's electricity distribution grid. Three additional farms in the cluster began operating covered lagoon digesters in January 2018. Each of these sites has a 1-MW reciprocating engine generator set for electricity generation. A second phase is planned in which generated biogas will be sent via low-pressure polyvinyl chloride (PVC) pipelines from each farm to a centralized hub for gas cleaning, conditioning, and pressurizing. From there, the upgraded gas will be injected into the local utility's natural gas pipeline or condensed for use as transportation fuel.

Lakeview Farms, one of the three most recent operating digester sites, is located within an 8-mile radius of 11 other diaries. It will serve as a mini-hub for electrical generation and a spoke for gas production. Seven new digesters are currently planned for the fuel-based phase of the cluster project, all of which will serve as additional spokes for biogas production. Of these, three digesters are in progress and expected to be completed in 2019.

Incentives and Funding

This project is receiving state-level incentives for construction, including pipeline construction and grants. For instance, the California Department of Food and Agriculture (CDFA) Dairy Digester Research and Development Program awards competitive grants to implement dairy digesters that result in long-term methane emission reductions on California dairies and minimize or mitigate adverse environmental impacts. In 2015, CDFA awarded a total of 4.8 million USD to the 3 Kern Cluster digesters that were most recently completed. The total cost of the three projects was 26.5 million USD. In 2017, CDFA awarded another 7.9 million USD for the next three digesters expected to reach completion in 2019. Projected costs for these three digesters total 22.1 million USD. There are also revenue incentives including the California Low Carbon Fuel Standard and the U.S. Renewable Fuel Standard.

5.4.6 – Philippines Tube Digesters

The 1991 volcanic eruption of Mount Pinatubo severely impacted croplands in the surrounding Philippine provinces. Local farmers in the province of Batangas, seeking to reestablish their farms, joined together to form the Buklod-Unlad Multipurpose Cooperative in 1992. Buklod-Unlad means "Unity for Progress."

With initial capital of only $100 and 44 members, the cooperative sought to support members by providing micro-loans. Today, with more than 2,000 members, the cooperative continues to help its members, not only with loans, but also with technological support to alleviate poverty and foster sustainability. The cooperative's mission is to better members' lives, alleviate poverty, promote family well-being, and maintain harmony within the community and the environment. With support from national and international partners, Buklod-Unlad began introducing AD technology to its members in 2011. This project represents a cooperative business model that could be implemented in the Indian market.

Cooperative Profile

The cooperative operates a swine breeding farm, a feed mill, and administrative offices. Through its "Paiwi" pig finishing project, the cooperative provides capital and 30 piglets to members who agree to raise the pigs per cooperative guidelines. The cooperative aids members in all areas of pig production, including financing, genetics, equipment, feed, and marketing; and the cooperative and the farmers share the proceeds from the market sales of the finished pigs and any offspring.

In consultation with the Global Methane Initiative, the Bureau of Animal Industry, the University of the Philippines, the Development Academy of the Philippines, and the Department of Science and Technology, Buklod-Unlad determined that tube-bag anaerobic digesters would be a cost-efficient and effective technology given the average size of member farms (approximately 30 pigs). To date, the cooperative has installed more than 20 tube-bag digesters both at its corporate breeding farm and at member farms. It has also assisted another cooperative (in Bulucan) with the installation of 4 tube digesters (2.2 diameter x 15 meters) and 2 gas holders on a farm with 500 sows.

AD System Installed at Bulucan Farm Cooperative

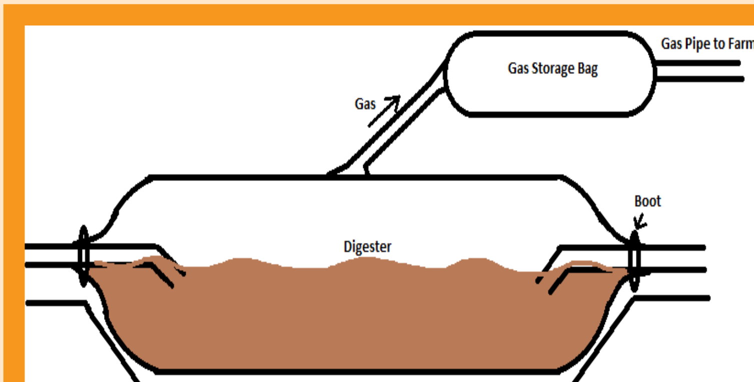
System components

While there is some variation in the individual systems, the digesters constructed by Buklod generally consist of the following elements:

- Mixing pit (optional)
- Tube bag digester
- Biogas storage bag
- Biogas engine (some sites)
- Gas handling system
- Biogas stove.

Mixing Pit (top) and Tube Digester (bottom)

Waste from the pig housing flows via a gravity conveyance system to a mixing pit. The mixing pit allows for the addition of more water if the waste is too thick for the digester. Waste is fed via pipe to the digester, which consists of two separate, tubular bags. Waste is collected in the first bag, and generated biogas flows to the second bag, where it is stored before exiting via an outlet pipe to the farm.



Simplified diagram of tube digester

Buklod used linear low-density polyethylene (LLDPE) geomembrane material for construction of both the tube bag digesters and the biogas storage bags. This material is flexible and easy to handle. Because the material can be rolled up or folded, Buklod can fabricate the digesters in its warehouse and transport them to the farm locations. Unlike other materials (such as PVC), this material offers resistance to ultraviolet light and can stand up well under intense heat and sun.

Biogas Use

All participating farms use the generated biogas for cooking. On Buklod's corporate site, the system generates enough cooking fuel for three families, in addition to powering an engine that provides lighting for the farm. Buklod retrofitted a car engine to run on the biogas generated from the digester.

The three families no longer need to purchase liquefied gas at a savings of approximately $5 per month. On the downside, the untreated biogas has resulted in some corrosion to the metal roof.

5.5 References

Arc Bio Fuel. Undated. Biovy Organic Manure. Manufacturers, Suppliers & Exporters. Arc Bio Fuel Private Ltd. Available: https://5.imimg.com/data5/HV/MI/MY-2918608/bio-cng.pdf. Accessed 5/29/2019.

EPA. 2004. *AgSTAR Handbook. A Manual for Developing Biogas Systems at Commercial Farms in the United States*, K.F. Roos, J.B. Martin Jr., and M.A. Moser (eds.). EPA-430-B-97-015. U.S. Environmental Protection Agency. February. Available: https://www.epa.gov/agstar/agstar-handbook. Accessed 5/29/2019.

Appendix A: Biogas Production Potential Calculations

To estimate methane potential emissions reductions from baseline waste management systems and potential methane production from AD systems, GMI used the methodologies described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC 2006 Guidelines*). This section describes the calculations and data used in the calculations.

GMI calculated the methane potential from manure using equation A-1:

$$CH_{4(M)} = \left(VS_{(M)} \times H_{(M)} \times 365 \text{ days/yr}\right) \times \left[B_{o(M)} \times 0.67 \text{ kg } CH_4/m^3 \text{ } CH_4 \times MCF_{S,k}\right] \quad \text{(A-1)}$$

where:

- $CH_{4\,(M)}$ = Estimated methane emissions from manure for livestock category *M* (kg CH_4 per year)
- $VS_{(M)}$ = Average daily volatile solids excretion rate for livestock category *M* (kg volatile solids per animal-day)
- $H_{(M)}$ = Average number of animals in livestock category *M*
- $B_{o(M)}$ = Maximum methane production capacity for manure produced by livestock category *M* (m^3 CH_4 per kg volatile solids excreted)
- $MCF_{(S,k)}$ = Methane conversion factor for manure management system *S* for climate *k* (decimal)

GMI calculated the methane potential for agro-industrial waste using equation A-2:

$$CH_{4(W)} = [(TOW_{(W)} - S_{(W)}) \times EF_{(W,S)}] - R_{(W)})] \quad \text{(A-2)}$$

where:

- $CH_{4\,(W)}$ = Annual methane emissions from agricultural commodity processing waste *W* (kg CH_4 per year)
- $TOW_{(W)}$ = Annual mass of waste *W* COD generated (kg per year)
- $S_{(W)}$ = Annual mass of waste *W* COD removed as settled solids (sludge) (kg per year)
- $EF_{(W,S)}$ = Emission factor for waste *W* and existing treatment system and discharge pathway *S* (kg CH_4 per kg COD)
- $R_{(W)}$ = Mass of CH_4 recovered (kg per year)

The methane emission factor in Equation A-2 is a function of the type of waste and existing treatment system and discharge pathway and is estimated using Equation A-3:

$$EF_{(w,s)} = B_{o\,(w)} \times MCF_{(s)} \qquad \text{(A-3)}$$

where:

$B_{0\,(W)}$ = Maximum CH_4 production capacity (kg CH_4 per kg COD) (0.25 kg CH_4 per kg COD)

$MCF_{(S)}$ = Methane conversion factor for the existing treatment system and discharge pathway (decimal

If the annual mass of COD generated per year (TOW) is not known and the needed data cannot be collected, the remaining option is estimation using Equation A-4, with country-specific wastewater generation rate and COD concentration data obtained from the literature. In the absence of country-specific data, values listed in Table A-5 can be used as defaults to obtain first order estimates of methane emissions.

$$TOW_{(w)} = P_{(w)} \times W_{(w)} \times COD_{(w)} \qquad \text{(A-4)}$$

where:

$P_{(W)}$ = Product production rate (metric tons per year)

$W_{(W)}$ = Wastewater generation rate (m^3 per metric ton of product)

$COD_{(W)}$ = Wastewater COD concentration (kg per m^3)

The data used to calculate methane potential and biogas production potential for each sector is presented below. For all calculations, methane is converted to CO_2e by multiplying by the global warming potential (GWP) of methane. For this report, GMI used a value of 25 for the methane GWP, based on IPCC estimates.

A.1 Dairy Manure

GMI used the data presented below to calculate the potential methane reductions for AD system development for dairy manure:

Variable	Description	Value			Notes
		Daily Spread	Burned for Fuel	Liquid Slurry	
$H_{(\#)}$	Total country average animal population, number of head		118,597,829		India Census data, including dairy cattle and buffalo
VS (kg/head/day)	Volatile solids excretion rate	2.6	2.6	2.6	Based on IPCC defaults
B_o (m^3 CH_4/kg VS)	Maximum methane production capacity	0.13	0.13	0.13	Based on IPCC defaults
MCF	Methane conversion factor	0.04	0.1	0.65	Based on IPCC defaults
%WMS	Percent of production in waste management systems	19%	51%	1%	Based on IPCC default estimates (excluding pasture and AD systems)
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	50%	50%	50%	GMI assumes 50% of dairy manure management not in pasture or AD systems could be replaced by AD
CH_4 (metric ton/yr)	WMS Methane emissions	37,808	253,709	32,335	Calculated using Equation A-1 and the %WMS and %WMS AD
Total CH_4 (metric ton/yr)	**Total methane emissions, CH_4**		323,852		Sum of methane from daily spread, burned for fuel, and liquid/slurry systems
Total CO_2 e (metric ton/yr)	**Total methane emissions, CO_2e**		8,096,293		Total methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The $H_{(\#)}$, VS (kg/head/day), B_o (m^3 CH_4/kg VS) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 35.5 percent of manure in baseline systems that would be replaced by AD systems ((19%+51%+1%) x 50%).
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 5,137 million m^3 of biogas per year.

A.2 Poultry Manure

GMI used the data presented below to calculate the potential methane reductions for AD system development for poultry manure:

Variable	Description	Value	Notes
$H_{(\#)}$	Total country average animal population, number of head	729,209,320	India Census data
VS (kg/head/day)	Volatile solids excretion rate	0.02	Based on IPCC defaults
B_o (m^3 CH_4/kg VS)	Maximum methane production capacity	0.24	Based on IPCC defaults
MCF	Methane conversion factor	0.015	Based on IPCC defaults
%WMS	Percent of production in waste management systems	50%	Based on IPCC default estimates
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	50%	GMI assumes 50% of poultry manure management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	3,258	Calculated using Equation A-1 and the %WMS and %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	81,445	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The $H_{(\#)}$, VS (kg/head/day), B_o (m^3 CH_4/kg VS) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 50 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 929 million m^3 biogas per year.

A.3 Sugarcane Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for sugarcane processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	348,000,000	Government of India 2018
W (m^3/metric ton)	Wastewater generation rate	11.0	GMI 2011
COD (kg/m^3)	Chemical oxygen demand	3.2	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management in open lagoons could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	122,496	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	3,062,400	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 328 million m^3 biogas per year.

A.4 Distilleries

GMI used the data presented below to calculate the potential methane reductions for AD system development for distilleries:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	3,550,500	USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	12.0	GMI 2011
COD (kg/m^3)	Chemical oxygen demand	110	GMI 2011
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.15	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	8,787	Calculated using Equation A-1 and the %WMS AD
Total CO_2e (metric ton/yr)	Methane emissions, CO_2e	219,687	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 125 million m^3 biogas per year.

A.5 Milk Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for milk processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	33,080,800	Milk production, National Dairy Development Board; 20% processed, Mehrotra et al. 2016
W (m^3/metric ton)	Wastewater generation rate	7.0	Based on IPCC defaults
COD (kg/m^3)	Chemical oxygen demand	2.7	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.15	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	1,172	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	29,308	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 17 million m^3 biogas per year.

A.6 Fruit and Vegetable Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for fruit and vegetable processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	5,635,040	Fruit and vegetables processed, National Horticulture Board; 2% processed, USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	20.0	Based on IPCC defaults
COD (kg/m^3)	Chemical oxygen demand	5	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	9%	GMI assumes 9% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	10,143	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	253,577	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 9 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 27 million m^3 biogas per year.

A.7 Cornstarch Production

GMI used the data presented below to calculate the potential methane reductions for AD system development for cornstarch processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	1,800,000	Production, USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	5.0	Expert judgment
COD (kg/m^3)	Chemical oxygen demand	20	Expert judgment
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	14%	GMI assumes 14% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	5,040	Calculated using Equation A-1 and the %WMS AD
Total CO_2e (metric ton/yr)	Methane emissions, CO_2e	126,000	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 14 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 13 million m^3 biogas per year.

A.8 Tapioca Production

GMI used the data presented below to calculate the potential methane reductions for AD system development for tapioca processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	79,200	Production, Government of India 2018; 1.6% tapioca turned into starch, GMI 2011
W (m^3/metric ton)	Wastewater generation rate	4.0	Expert judgment
COD (kg/m^3)	Chemical oxygen demand	11	Expert judgment
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	17%	GMI assumes 17% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	118	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	2,962	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 17 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 0.3 million m^3 biogas per year.

A.9 Crop Residues

GMI used the data presented below to calculate the potential methane reductions for AD system development for crop-residues:

Variable	Description	Value	Notes
W (million ton/year)	Surplus crop-residues production, country total	178	TIFAC & IARI data (2018)
VS (kg/kg of crop residues)	Volatile Solids rate	0.70	USDA (2008)
B_o (kg CH_4/kg VS)	Maximum methane production capacity	0.36	Contreras et al. (2012), Yan et al. (2017)
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	25%	GMI assumes 25% of crop-residues could be replaced by AD

GMI calculated the biogas production using:

- The W (million metric ton/year), VS (kg/kg crop residues), and B_o (kg CH_4/kg Vs) shown above, and
- An assumption that 25 percent of crop residues could be replaced by AD (%WMS AD).
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 29,983 million m^3 biogas per year.

Appendix B: Indirect Emissions Reduction Calculations

GMI used the electricity generation potential of biogas and the emissions rate associated with the offset fuel source to estimate indirect emissions reductions from offsetting electricity generation from traditional fossil fuels. GMI assumed that the biogas would replace coal as the fuel for electricity generation. This section describes the calculations and data used in the calculations.

GMI calculated the electricity generation potential from biogas using equation B-1:

$$\text{Elec. Gen. Potential} = CH_4 \text{ Production Potential} / \text{Methane Density} \times CH_4 \text{ Heat Content} / \text{Btu to Wh Conversion} \times \text{Engine Efficiency} \times \text{Online Efficiency} / \text{Wh to kWh Conversion} \quad \text{(B-1)}$$

where:

Elec. Gen. Potential	=	Electricity generation potential from biogas (kWh/year)
CH_4 Production Potential	=	Methane production potential (MT CH_4 per year)
Methane Density	=	Density of methane (metric ton CH_4/ft^3 CH_4)
CH_4 Heat Content	=	Heat content of the methane (Btu/ft^3 CH_4)
Btu to Wh Conversion	=	Energy conversion factor from British thermal units to watt hours (Btu/Wh)
Engine Efficiency	=	Assumed engine efficiency (%)
Online Efficiency	=	Assumed online efficiency (%)
Wh to kWh Conversion	=	Energy conversion factor from watt hours to kilowatt hours (Wh/kWh)

GMI calculated the indirect emission reductions using Equation B-2:

$$CH_4 \text{ Reductions}_{Indirect} = \text{Elec. Gen. Potential} \times CO_2 \text{ Emission Reduction} \quad \text{(B-2)}$$

where:

CH_4 Reductions$_{Indirect}$	=	Indirect emission reductions from replacing coal with biogas for electricity generation (MT CO_2 per year)
Elec. Gen. Potential	=	Electricity generation potential from biogas (kWh/year)
CO_2 Emission Rate	=	CO_2 emissions rate from generating electricity with coal (kg CO_2/kWh generated)

Using equation B-1, GMI calculated that 14.8 million metric tons of CO2e could be reduced due to avoided coal-generated power plant emissions.

B.1 Indirect Emissions Values

GMI used the following assumptions and conversion factors to calculate the indirect emissions reductions from biogas use for electricity generation:

- Methane density: 1.92E-05 metric ton CH_4 per ft^3 CH_4
- Assumed heat content of methane: 923 Btu/ft^3 CH_4
- Energy conversion factor: 3.413 Btu per Wh
- Assumed engine efficiency: 0.35
- Assumed online efficiency: 0.9
- Energy conversion factor: 1000 Wh per kWh

GMI then used the above assumptions with the methane production potential calculated in Appendix A to determine electricity generation potential and indirect emissions reductions:

Sector	Methane Production Potential (MT CH_4 per year)	Electricity Generation Potential (kWh per year)	Indirect Emissions Reduction (MT CO_2e per year)
Dairy Manure	2,825,619	12,536,846,095	12,787,583
Poultry Manure	347,500	1,541,806,792	1,572,643
Sugarcane Processing	122,496	543,496,367	554,366
Distilleries	46,867	207,940,070	212,099
Milk Processing	6,252	27,740,389	28,295
Fruit and Vegetable Processing	10,143	45,003,288	45,903
Cornstarch Production	5,040	22,361,724	22,809
Tapioca Production	118	525,692	536

B.2 Other CO_2 Emission Reduction Values

Indirect emissions reduction from offsetting other fossil fuels can be calculated by using an appropriate emissions rate. In India, the electricity sector generation mix is comprised of thermal plants (60 percent), hydroelectric plants (34 percent), and nuclear plants (6 percent; GMI 2011). The principal fuels used by thermal plants are coal, fuel oil, and natural gas. The table below shows the associated carbon emissions rate for each fuel type.

Fuel Replaced	CO_2 Emission Reduction
Coal	1.02 kg/kWh generated
Natural gas	2.01 kg/m^3 CH_4
LPG	2.26 kg/m^3 CH_4
Distillate fuel oil	2.65 kg/m^3 CH_4

Source: GMI 2011