



PRACTICAL BIOGAS PLANT DEVELOPMENT HANDBOOK

*Potential Biogas resources, Legal Review,
and Good Practice of Biogas Construction
in Cambodia*



Prepared by:



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HANDBOOK: Potential Biogas resources, Legal Review, and Good Practice of Biogas Construction in Cambodia

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LIST OF ABBREVIATIONS

ABP	Anaerobic bio-gasification potential
ABR	Anaerobic Baffled Reactor
AC	Anaerobic contact
AD	Anaerobic digestion
BCAs	Biodigester Construction Agents
BIOMA	Biogas Institute of Ministry of Agriculture and Rural Affairs
BOD	biological (biochemical) oxygen demand
BSE	Bovine Spongiform Encephalopathy
BTIC	Biogas Technology and Information Center
CAMDA	China Agricultural Machinery Distribution Association
CAPEX	Capital expense
CEDAC	The Cambodian center for study and development in Agriculture
CHP	Combined heat and power
CNG	Compression natural gas
COD	Chemical oxygen demand
COMFAR	Computer Model for Feasibility Analysis and Reporting
CSP	Chemical scrubbing process
C/N	Carbon to nitrogen
DAL	Department of Agricultural Legislation
DM	Dry matter
CS	Cryogenic separation
CSP	Chemical scrubbing process
ERDI	Energy Development and Research Institute of Chiang Mai University, Thailand
FM	Fresh manure
FTB	The Foreign Trade Bank of Cambodia
FvB	German Biogas Association
GEEW	Gender equality and the empowerment of women
GEF	Global Environment Facility
GHG	Green House Gas

HPWS	High pressure water scrubbing
HRT	Hydraulic retention time
IFAD	International Fund for agricultural Development
IRR	Internal rate of return
KEPCO	Korean Electric Power Corporation
MAFF	Ministry of Agriculture, Forestry and Fisheries
MEF	Ministry of Economy and Finance
MIH	Ministry of Industry and Handicraft
MoE	Ministry of Environment
MME	Ministry of Mines and Energy
MS	Membrane separation
MSW	Municipal solid waste
NBP	National biogas program
NPV	Net present value
LCA	Life cycle assessment
LoA	Letter of Agreement
LPG	Liquefied petroleum gas
ODM	Organic dry matter
OFMSW	Organic fraction of municipal solid waste
OLR	Organic loading rate
OM	Organic matter
OPEX	Operating expense
PBPO	Provincial Biodigester Program offices
Ppm	Part per millions
PSA	Pressure swing adsorption
RE	Renewable Energy
RETs	Renewable Energy Technologies
RUA	Royal University of Agriculture
SNV	Stichting Nederlandse Vrijwilligers
S-RET	Scaling-up of Renewable Energy Technologies
SRT	Solid retention time
TKN	Total Kjeldahl nitrogen
TSS	Total suspended solid
TU	Technical University of Vienna

TWAS	Thickened Waste Activated Sludge
UNIDO	The United Nations Industrial Development Organization
VS	Volatile solids
VFAs	Volatile fatty acids
VSS	Volatile suspended solid
Wh/y	Watt hour per year

LIST OF SYMBOLS

Ca(OH)_2	Calcium hydroxide
CH_4	Methane
CO	Carbon mono oxide
CO_2	Carbon dioxide
Fe_2O_3	Iron oxide or ferrous oxide
$\text{Fe(NH}_4)_2(\text{SO}_4)_2$	Ferrous ammonium sulfate
H_2	Hydrogen
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
$\text{K}_2\text{Cr}_2\text{O}_7$	Potassium dichromate
N_2	Nitrogen
Na_2CO_3	Sodium carbonate
NaOH	Sodium hydroxide
NH_3	Ammonia
PAHs	Polycyclic aromatic hydrocarbons
SO_2	Sulfur dioxide
ZnO	Zinc oxide

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PREFACE

Cambodia is working on a RE strategy that lays down the policy intention, objectives, and guidelines for developing the requisite infrastructure for providing renewable electricity services in rural areas. The development of bioenergy offers significant possibilities for reducing greenhouse gas (GHG) emissions and fossil fuel dependency. New regulations for environmental protection have promoted the biogas plant using anaerobic digestion (AD) from organic wastes such as animal manure and crop residues and organic residues from food and agro-industries to generate renewable energy. As feedstocks become the dominant source of biogas, reducing energy used and GHG emissions will benefit everyone, especially farm owners, developers, and communities.

Stichting Nederlandse Vrijwilligers (SNV) had been working on disseminating household-sized biodigesters and supporting the National Biodigester Programme (NBP) in distributing more than 10,000 biodigesters across the country. According to the report from UNIDO, all pig farms and agro-industry in Cambodia can produce electricity around 60 Twh/y and 2,070 Twh/h through the biogas project. Recently, the commercial farm and agro-industry have dramatically increased. UNIDO supports the farms that plan to build commercial biogas plants through the global environmental facility (GEF) project's "Reduction of GHG emission through promoting commercial biogas plants in Cambodia." Based on the feasibility studies of NBP and BTIC (Biogas Technology and Information Center), there are many potential farms and industrial waste that can produce biogas and electricity through commercial biogas plant. The present volume on biogas would assist the scientific and industrial communities in further developing this industry worldwide.

This biogas handbook mainly focuses on the practical biogas plant for further development of commercial biogas plant in Cambodia. This book also describes potential resources, biogas technology, legal review, and good practice of biogas construction. The handbook is divided into nine chapters, which target readers, such as researchers, farm owners, investigators, developers, policymakers, and financial institutions. Chapter 1 gives an overview of biogas plant and biogas production. The benefits and limitations of the biogas plant are discussed. Chapter 2 provides the biogas status and general information about the biogas systems and technologies used in Cambodia. Strength, Weakness, Opportunities, and Threats (SWOT) analysis of

commercial biogas in Cambodia is discussed. Chapter 3 describes how the biogas system works (from feedstock to biogas generation and electricity conversion). The three main categories of biogas resources (agriculture, municipal, and agro-processing industry wastes) and their composition, quality, availability are presented. Chapter 4 focuses on planning, design, and suitable technology and selecting the size of equipment for the biogas resource to reduce financial investment and get more economic benefit from the biogas project. Chapter 5 discusses the utilization of biogas as electricity, heat, and biofuel, whereas the utilization of by-products of biogas (digestate) as organic fertilizer in Cambodia is highlighted in Chapter 6. An example of electricity production from an existing biogas plant in Cambodia is also given in this chapter. Chapter 7 indicates the economic assessment and financial analysis of biogas projects such as total investment cost, revenue, internal rate of return (IRR), and payback period. A feasibility study from BTIC on the technical and financial assessment of a pig farm is also discussed. Chapter 8 describes the number of risks, risk assessment, and safety of biogas production. Health and safety issues, and safety systems, guidelines, and documents are included. Finally, chapter 9 highlights the legal aspects (frameworks and policy), environmental aspects (regulations and impacts), and social aspects.

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CHAPTER 1: INTRODUCTION TO BIOGAS PLANT FUNDAMENTALS

This chapter gives an overview of biogas and a perspective of biogas and describes all essential conditions for biogas production. Two central biogas systems, household biogas and commercial biogas plant, and their biogas production and utilization are introduced. Biogas has advantages and limitations, so the benefits of biogas production on the environment, companies, and farmers are included in this chapter.

1.1 Overview of biogas

Biogas is formed naturally from biogenic matter under anaerobic conditions. In nature, this occurring biogas escapes into the atmosphere, where methane's main component contributes to global warming. Since the 1930s, a standard biogas process from sewage sludge has been used in household and farm-scale applications. Since the start of the twenty-first century, policymakers have recognized that biogas production can answer some challenges in reducing greenhouse gas (GHG) emissions such as methane from slurry storage and impacts of pollution by waste disposal. Mainly, it can provide a renewable source of energy. This recognition has led to the rapid growth of the biogas sector and has been promoted through legislation with various targets set worldwide for renewable energy and reduced GHG emissions (Gomez and Costa 2013). Although biogas becomes a vital energy component for sustainability transition, the total production volume of biogas is still relatively low compared to other renewable energy such as solar cell and wind power. Both developed and developing countries face some barriers, including technical, economic, market, institutional, socio-cultural, and environmental, that hinder the widespread adoption of biogas as a source of energy. The biogas industry faces the most frequent and crucial constraints that were identified and integrated into a systematic classification (Nevzorova and Kutcherov 2019).

Given the potential and clear perspective for converting biomass residues and other organic material into bioenergy, it is no surprise that biogas production is growing. The number of biogas installations is estimated at more than 35 million, most of which are household installations located in China and India. In contrast, large farm digesters, primarily found in Europe and North America, and industrial facilities have a much larger average capacity (Langeveld et al. 2016). It has been estimated that biomethane production by the year 2020 will achieve 250 billion standard cubic meters

(Nm³) (Matheri et al. 2017). Therefore, biomethane has become one of the most used biofuels for power generation and heating purposes in society today.

Anaerobic digestion (AD) has emerged as one of the established, clean, and renewable energy technology for the production of methane-rich biogas (Rana et al. 2020). A proper biogas facility of the biogas process can be fully contained, controlled, optimized, and commercially viable industry.

Table 1 Number of biogas installations (Langeveld et al. 2016).

Region	Number of installations (Year)	Region	Number of installations (Year)
Europe		Asia	
Austria	337 (2013)	China	30 million (2010)
Denmark	154 (2012)	India	4.2 million (2011)
Germany	7,850 (2013)	Nepal	1.3 million (2012)
Italy	1,264 (2013)	Pakistan	5,360 (2008)
Netherland	252 (2013)	South Korea	82 (2013)
Sweden	264 (2013)	Vietnam	23,300 (2012)
Switzerland	606 (2013)	Africa	
UK	634 (2013)	Burkina Faso	3,500 (2015)
Europe (all)	14,563 (2013)	Ethiopia	10,109 (2015)
America		Kenya	14,112 (2015)
United States	2,116 (2014)	Tanzania	10,000 (2015)
Brazil	25 (2012)		

Biogas is a product of the biochemical decomposition of organic materials. It consists mainly of methane (50–75%), carbon dioxide (25–50%), and water vapor. It may also contain small quantities of nitrogen, hydrogen sulfide, ammonia, and other trace gases. Such elements like Nota Bene (NB), N₂, and O₂ are there if air has been introduced in the gas holder, as there are naturally not produced through AD. Sulfur can be found in the sludge but not in the biogas. H₂ is an intermediary product in the AD process, not typically in the end product. For certain gases (e.g., landfill gas), siloxanes and dust can be found. Components like CO, Polycyclic aromatic hydrocarbons (PAHs), and halogens are usually below the detection limits (Ullah Khan

et al. 2017). The percentage of biogas production is dependent on the various feedstock characteristics. Many materials, including agricultural wastes (biomass), food waste, industrial waste, and wastewater, are feedstocks for biogas production.

However, not all waste products and crops are equally suitable for biogas production, and in some cases, biogas production might not be profitable. To assess the suitability of biogas feedstocks, a reliable way of characterizing and analyzing feedstocks is necessary. A preliminary feedstock assessment can be carried out using data available in literature combined with feedstock process and production data. Legal issues should also be considered, such as environmental and safety laws regulating the use of waste products. A detailed laboratory analysis should follow if the preliminary assessment indicates that the feedstock might be suitable (Drosg et al. 2013).

Concise information about the different analysis methods such as total solids (TS), volatile solids (VS), chemical oxygen demand (COD), biological (bio-chemical) oxygen demand (BOD), nitrogen content, C/N ratio, and presence of inhibitory substance needs to be carried out. The type of biogas plant, such as reactor design and operational conditions, needs to be designed based on the available feedstocks. Biogas production potential should also be investigated through various methods as a crucial step in planning a biogas plant (Jingura and Kamusoko 2017).

1.2 Basic conditions for biogas production

Biogas is produced during the breakdown of organic matter in the absence of oxygen (anaerobically). Biogas has from anaerobic digestion with methanogen or anaerobic organisms, which digest material inside a closed system or ferment biodegradable materials. This closed system is called an anaerobic digester, biodigester, or bioreactor. Biogas can be produced through anaerobic digestion (AD) by consortia of bacteria and archaeobacteria (Ghodrat et al. 2018).

The process of anaerobic decomposition involves a series of metabolic reactions comprising (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis (Figure 1). The initial hydrolysis and the acid-producing stages separate from methanogenesis. The degradation of organic matter (OM) occurs in individual steps carried out by different microorganisms in different requirements in the fermentation environment (Demirel and Yenigün 2002). The early stages require acidic operating conditions, while CH₄ produces in later neutral conditions (Jingura and Kamusoko 2017). Initially, the complex biopolymers (carbohydrates, proteins) and other large

molecules (fats) are broken down into simpler molecules (sugars, fatty acids, and amino acids) in a hydrolysis step. Bacteria known as acidogenic in an acidogenesis action produce volatile fatty acids (VFA) and alcohols and other by-products such as sulfide, carbon dioxide, and ammonia. Methanogenesis is a critical step in the entire AD process as it is the slowest biochemical reaction. At the final stage, methanogens utilize H_2 , CO_2 , and acetate, which are produced during acidogenesis and acetogenesis steps, to produce methane in two ways: using cleavage of two acetic acid molecules to generate CH_4 and CO_2 , or by reducing CO_2 with H_2 (Monnet 2003). In AD, the acid-forming and the methane-forming microorganisms differ widely in physiology, nutritional needs, growth kinetics, and sensitivity to environmental conditions (Chen et al. 2008). Failure to balance these two groups of microorganisms is the primary cause of reactor instability (Demirel and Yenigün 2002). Inhibitory substances in sludges or wastewater are often the leading cause of anaerobic reactor upset and failure. A wide variety of substances such as arsenic, mercury, silver, and uranium have been reported to inhibit the AD processes (Mudhoo and Kumar 2013). Material may judge inhibitory when it causes an adverse shift in the microbial population or inhibition of bacterial growth. Inhibition is usually indicated by a decrease in the steady-state rate of methane gas production and accumulation of organic acid (Jingura and Kamusoko 2017).

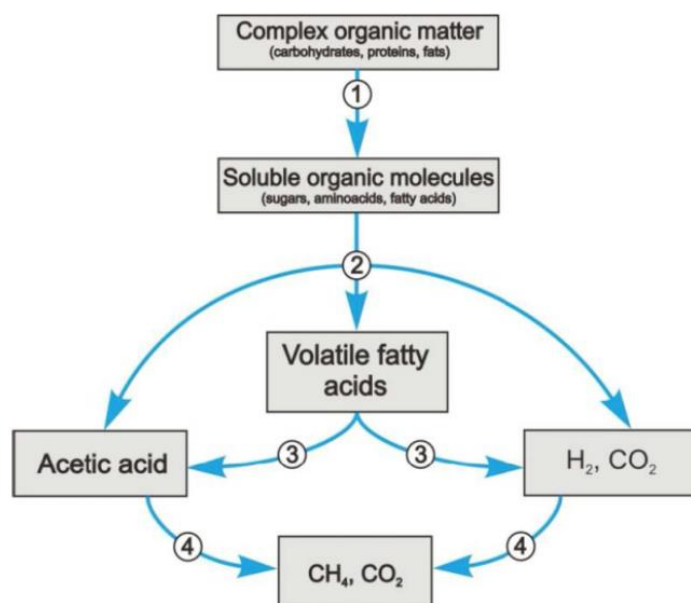


Figure 1 Anaerobic pathway of digestion of organic material.

1.3 Biogas system

Biogas plants categorize into small and large-scale plants. Small-scale biogas plants can be domestic, household, decentralized, farm, or communal biogas. These plants are employed mainly in rural areas and have low investment costs. There are three central systems for household biogas: fixed dome plant, floating drum plant, and balloon/bag digester (Huber 2019). Small-scale biogas production units can be designed and successfully operated even in settings where means for advanced technology equipment are low and institutional capacities are limited. The household accesses sufficient organic feedstocks such as cattle, pig, and chicken manure or human waste and kitchen waste. They are considering the biogas yield of different livestock. Biogas is used as gas for stove-top cooking, whereas digestate has high quality liquid fertilizer. It is mainly in emerging and developing economies, where it helps households through its numerous social, environmental, health, and economic benefits. Biogas reduces workload, mainly for women, in firewood collection and cooking and saves money (Patinvoh 2017; Nevzorova and Kutcherov 2019).

On the contrary, large-scale plants or commercial biogas plants require significant feedstock obtained from large-scale agricultural waste, municipal organic waste, industrial waste, or energy crops. Commercial biogas plants have high investment costs depending on the scale. These plants also require high technology, and financial, economic, legal, environmental, and social aspects need to be considered prior to start biogas plant construction. Based on the available feedstocks, the biogas and electricity production, payback period, and total investment cost can be estimated through feasibility studies from a biogas consultant. Proper planning of a biogas project is essential to ensure that the owners have enough finance to build the biogas plant and get profit from that project. Biogas often uses for producing electricity and heat depending on the demand. A transport fuel biogas must be upgraded to at least 95% methane by volume in vehicles or filling stations. In the case of biogas for cooking purposes, the biogas needs to be distributed to single households by filling and transporting the biogas or biomethane in biogas backpacks, in high-pressure gas cylinders, or by biogas pipelines. The by-product of biogas uses as organic fertilizer or soil improver that returns essential nutrients to the soil (Bolin 2009).

1.4 Advantages of biogas

Biogas systems turn the cost of waste management into a revenue opportunity for farms, dairies, and industries. Converting waste into electricity, heat, or vehicle fuel provides a renewable energy source that can reduce dependence on foreign oil imports, reduce greenhouse gas emissions, improve environmental quality, and create local jobs. Biogas systems also provide an opportunity to recycle nutrients to the food supply system, reducing the need for both petrochemical and mined fertilizers. Biogas adds value to organic wastes and by-products and contributes to energy supply in the country, opportunities for the agricultural sector, and technology supply sector. Biogas plants have many benefits to the users, farm owners, investors, and society.

1.4.1 Benefits for environmental protection

Biogas serves its best for environmental protection such as GHG reduction, avoidance of methane emissions, the substitution of fossil energy, nutrient recycling, and odor reduction. Gas generated through bio-digestion is non-polluting; it reduces greenhouse emissions. Although CO₂ forms when biogas is combusted, this amount equals the amount of CO₂ used to produce the organic material converted during the anaerobic digestion process. There is zero emission of greenhouse gasses to the atmosphere; therefore, using gas from waste as a form of energy is a great way to combat global warming. Concern for the environment is a significant reason why the use of biogas has become more widespread. Biogas plants significantly curb the greenhouse effect: they lower methane emissions by capturing this harmful gas and using it as fuel. Biogas generation helps reduce reliance on fossil fuels, such as oil and coal (Seadi et al. 2008). The climatic protection goal (reduced GHG emission and mitigation of global warming) is effectively supported by biogas production (Deublein and Steinhauser 2010).

1.4.2 Financial and economic benefits

Production of biogas from AD requires work power for production, collection, and transport of AD feedstock, manufacture of technical equipment, construction, operation, and maintenance of biogas plants. It will create a business opportunity for a company to establish new enterprises on the biogas project. On the other hand, it can benefit the project owner to add value from waste products by turning to electricity and organic fertilizer, thus reducing energy costs and the return on their investment (Seadi et al. 2008).

1.4.3 Farmers and society benefits

Biogas from biomasses and manure wastes use as electricity and heat for the farm owners or communities in rural areas that do not have access to the electricity grid (Gomiero 2016). Waste collection and management significantly improve in areas with biogas plants. It improves hygienic conditions because AD deactivates pathogens, parasites, and worm eggs and flies, reducing waterborne diseases. Landfill areas will decrease due to cutting down overflowing landfills that spread foul smells and allow toxic liquids to drain into underground water sources. The by-product of the biogas generation process enriches organic (digestate), which is a substitute for chemical fertilizers. The fertilizer discharge from the digester can accelerate plant growth and resilience to diseases. On the contrary, commercial fertilizers contain chemicals that have toxic effects and can cause food poisoning, among other things (Baredar et al. 2020). Significantly, digestate from animal manure has improved fertilizer efficiency compared to raw animal manure due to higher homogeneity and nutrient availability. This digestate is a valuable soil fertilizer, rich in nitrogen, phosphorus, potassium, and micronutrients, which apply to soils with the standard equipment for applying liquid manure. If plants use as co-substrates for biogas production and the residues recycle for agriculture, no mineral fertilizer is needed. Their nutrients can recycle while reducing nitrate leaching. Plant compatibility and plant health improve, and therefore biogas production is subsidized in many countries, giving the farmer an additional income (Deublein and Steinhauser 2010).

1.5 Limitations of biogas

Biogas technology has many competitors such as micro hydropower, solar systems, and other renewable energy due to the lack of advanced technology and investment cost. Biogas technology today is not a universally applicable technology. It is challenging to introduce biogas technology to a large share of the population. Some types of biogas systems, for example, lagoons, require large land. Not all organic wastes are equally suitable for biogas production, and in some cases, biogas production might not be profitable. There are only a few that can convert into simple and low-cost biogas systems. Advanced biogas systems are more complex and have high investment costs.

The investment cost is high compared to diesel from fossil fuel, especially for the small biogas plant. Especially smaller biogas systems have a long payback period,

making the farmers or investors hesitate to invest in the biogas plant. Operation and maintenance costs are relatively high, and the life span of some equipment is limited. Depending on the local conditions and the available feedstocks, the electricity from biogas may not be competitive with grid electricity. Alternative means of biogas use (e.g., upgrading and bottling) are hampered by market demand and thus limit the widespread application and promotion of biogas production (Khayal 2019).

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CHAPTER 2: BIOGAS STATUS IN CAMBODIA

This chapter indicates the critical challenges in energy production and general information about establishing biogas systems in Cambodia. The two central biogas systems existing in Cambodia are household and commercial biogas plants. This chapter emphasizes biogas status and commercial biogas perspective in rural areas and highlights SWOT analysis for commercial biogas in Cambodia.

2.1 Key challenges and sustainable strategy in the energy sector in Cambodia

Cambodia has undergone rapid economic development in recent decades; however, the country still lacks the infrastructure required for the energy sector to match the pace of development. Cambodia's energy production relies heavily on imported fossil fuel and imported electricity from nearby countries such as Vietnam, Thailand, Laos, and other electricity resources: hydropower, solar, and biofuels from biomass and biogas (Figure 2). Electricity prices are high compared to the region, especially in the rural areas where diesel generators use as a power source. Electricity demands are increasing at a surprising rate in many districts and provinces serviced by Government coordinated electrification programs. The basis for this progress is a ready market for the sale of electricity by the local entrepreneurs, but the state electricity companies alone cannot meet the increasing electricity demand (Mika et al. 2021).

As the population increases and industry expands, Cambodia's electricity consumption increases (Figure 3) (MME 2016). For sustained economic and industrial development, it needs a good forecast of long-term energy demand. Energy supply options must also review to ensure adequate energy supply capacity to major strategic industrial zones. According to World Bank and KEPCO (Korean Electric Power Corporation), the electricity demand projection in Cambodia in 2024 will be 3,045 MW and 16,244 GWh for capacity and electric energy, respectively (Gutaman et al. 2006). Energy security facilitates a country's socio-economic growth and sustainability. Energy supply and access are fundamental to achieving developmental goals. Options such as hydropower and coal-fired power plants can have a high environmental impact. On the other hand, renewable energy from biogas is clean and significantly curbs the greenhouse effect (lower methane emissions). So, bioenergy development offers significant possibilities for reducing GHG emissions and fossil fuel dependency (Kumar 2019).

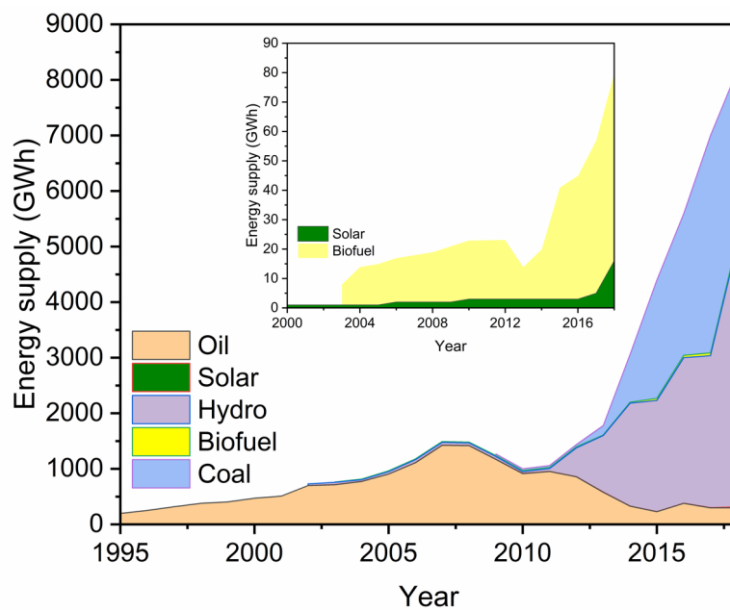


Figure 2 Energy supply in Cambodia from 1995 to 2018 by sources: Oil, solar, hydro, biofuel, and coal.

The laws and policies on the development of the energy sector must adapt to the energy demand. On the other hand, cooperation and participation from stakeholders, including ministries and other governmental agencies, development partners, and private investors, have played a significant role. This strategy exploits new opportunities driven by rapid urbanization and growing middle-class with high disposable income, developing and modernizing the agricultural sector. New regulation for environmental protection promotes the biogas plant using AD of organic waste of farm origins such as manure, crop residues, and organic residues from food and agro-industries to generate renewable energy and control the application of land animal manure. The manure residues have long been identified as a major source of environmental pollution. The animal farms release unpleasant smell which affects the neighboring farmers and pollutes the environment. These wastes traditionally have been disposed of, directly or after composting, as soil amendments in agriculture. The AD process can reduce environmental pollution by preventing methane into the atmosphere while burning methane and releasing carbon-neutral carbon dioxide (no net effect on atmospheric carbon dioxide (CO₂) and other GHG). As manure feedstocks become the dominant source of biogas over decades, reducing energy used and GHG emissions will benefit everyone, especially farm owners and people in rural

communities. Farmers could save hundreds to thousands of dollars every year from reduced energy use by installing biogas plants at their farms (NBP 2019).

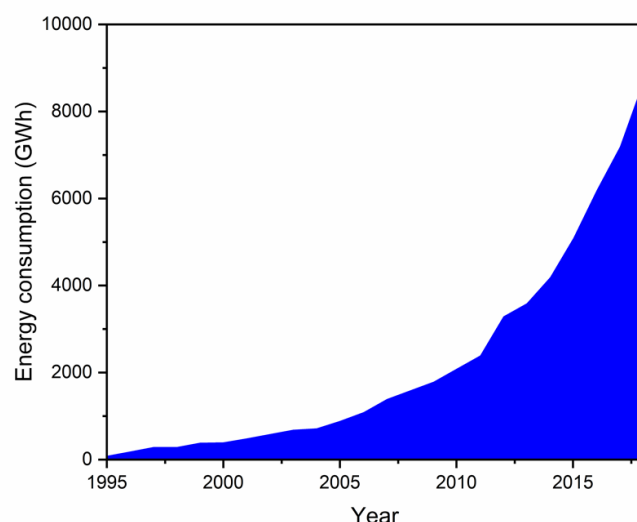


Figure 3 Electricity consumption in Cambodia from 1995 to 2018.

2.2 General information of biogas (biodigester) in Cambodia

Biodigesters play an essential role in reducing GHG emissions from animal production into the environment by managing animal livestock waste. Cambodia has a favorable environment and conditions for disseminating biogas Technology, yet this potential has not been achieved. This technology is relatively new in Cambodia in comparison to its neighboring countries. There was a lack of technical and financial support, knowledge, experience, skilled personnel, and manufacture. Therefore, to develop biogas projects, investors need to import most of the equipment and expertise from other countries leading to relatively higher investment costs and making a challenge in operation and maintenance of the equipment. From 1986 to 2005, 400 domestic digesters were built in Cambodia by international aid agencies. Most of these digesters were plastic tube types, either comprehensively subsidized or wholly paid for by contributors or foreign agencies (McIntroh 2004). These digesters have a brief life span, and because of a lack of technical support, and a practical, marketable model, most of these digesters went quickly out of operation.

For this reason, in 2006, the Cambodian National Biodigester Program (NBP), one of the first large-scale biogas projects, has been implemented in the history of unsuccessful biodigester in the past. This program was managed by MAFF and SNV Netherlands development organization and executed by the Department of Animal Production and Health (Patinvoh and Taherzadeh 2019). This offset project investment is needed to make biogas installations available in Cambodia to increase rural access to a sustainable clean energy supply. The NBP's original goal was to create a self-financing biodigester market in Cambodia. The long-term goal was to build national capacity to technically and financially carry forward the project without SNV (Buysman 2015).

According to the development of animal husbandry, the management of feedstock is highly considered through the extension of animal raising and the building of biodigesters at animal farms and families raising animals. All relevant stakeholders were encouraged to participate in implementing policy on biodigester development to make farmers and rural communities get healthy, better livelihood. It expects to provide environmental sustainability by scaling up animal production and biodigesters in Cambodia (Hyman and Bailis 2018). The progress of biodigester introduction has gone through many stages of development. A national non-governmental organization, the Cambodian center for study and development in Agriculture (CEDAC), hosted four additional provincial offices, which created 14 Provincial Biodigester Program offices (PBPO) nationwide. These offices are responsible for the training of Biodigester Construction Agents (BCAs) and engage microfinance institutions to access loans for the farmers (Hyman and Bailis 2018).

In 2015, MAFF set a technical working group for preparing strategic frameworks and policies on biodigester development to promote biodigester construction with animal production and enhance biodigester technology extension and the operation of biodigesters. The procedures and strategies aim to respond to the context of progress and actual demand related to promoting biodigester development and practical and sustainable use. Four strategic measures are imposed, including 1) increase the education and dissemination to all animal farm owners about the benefits of biodigester on social and economic welfare and on the environment; 2) Encourage farm owners to build the standard biodigester; 3) Inspire farm owners to apply development approach "Linkage of animal farms with the integrated farming system" to improve the animal production and organic agricultural production, and 4) increase

incentives to farm owners via providing of certificate of appreciation depending to the standard of their applied biodigesters. Promoting commercial biogas plants will help Cambodia intelligently utilize biogas to produce electricity and reduce GHG emissions to support the country's sustainable development (MAFF 2016).

2.3 Biogas household

In rural areas (around 80% of the total population), Cambodians have less access to modern energy sources such as gas and electricity. The primary fuels used for cooking and lighting in households are firewood (83.6%), charcoal (7.5%), and LPG. Women and children are strongly affected by indoor air pollution, causing a range of diseases due to the prevalent use of traditional cooking techniques. Therefore, arguments for promoting biodigester programs include reducing the burden of women's work (SNV 2006; MAFF 2016). The family system in rural areas is an integrated livestock-rice cultivation system, where rice production relies on draught animal power (cattle or buffaloes). Most families have at least a few chickens and pigs or cow, and a tremendous potential for biogas of around 1 million domestic biodigesters was estimated (Kooijman 2014). Domestic biodigesters are a simple construction that can covert human excrement, biomass, or animal dung into small but valuable quantities of biogas. Among domestic or household digesters, fixed dome digesters are the most popular design in Cambodia because of their low maintenance requirement, reliability, and ease of construction using stones, brick, clay, and cement. Lifespan is more than 20 years as the constructed underground can protect it from physical damage or erosion (Hessen 2014).

In December 2018, over 27,000 fixed dome biodigesters were constructed in 15 provinces. The trend of biodigesters among rural farmers has slightly increased (Hyman and Bailis 2018). Critical success factors are the construction services, technical after-care, and access to finance. Biogas loans can make through a special agreement from local banks and credit unions. Since 2010, over 70% of households have used a biogas loan to finance their biodigester within two years of the payback period.

Furthermore, the NBP project has granted 15% of total biodigesters construction to more than 3,500 households. Therefore, the farmer's expenditure reduces through building biodigesters. The total construction cost and the biogas production depend on biodigester size (Table 2). Other development partners have been

concerned with implementing NBP and increasing resources, both technical and financial support.

Table 2 Construction cost of household biodigester in Cambodia (NBP 2019).

Biodigester size (m ³)	Construction cost (USD)	Subsidy from NBP (USD)	Farmer's expenditure (USD)	Time for one stove (hour)	Time for one lamp (hour)
2	304	150	154	1 – 2	4 – 8
3	381	150	231	2 – 3	8 – 12
4	490	150	340	2 – 4	8 – 16
6	550	150	400	4 – 6	16 – 24
8	720	150	570	6 – 8	24 – 32
10	810	150	660	8 – 10	32 – 40
15	1100	150	950	10 – 15	40 – 60

Biodigesters International ATEC (supporting from the Private Financing Advisory Network (PFAN) in 2017) is a Cambodia-based social enterprise that provides high-quality, prefabricated biodigesters to rural households. A 4m³ digester can accommodate waste from 2 to 3 cows or 4–6 pigs, and it can provide enough gas to meet all daily cooking needs and produce 20 tons of high-quality organic fertilizer per year. The units help farmers save up to \$521 per year on gas and fertilizer, reducing their dependence on firewood and preventing deforestation (ATEC 2021).

2.4 Commercial biogas plant

Commercial biogas plants were expected to install across the country to provide electricity in rural areas without the national grid. NBP has reported that there are 44 commercial biogas plants in Cambodia. Most of them are used in mixed farms, fattening, dairy and pig farms, and the starch industry (NBP 2019). The biogas technology used is mainly simple and improved covered lagoons due to the low investment and maintenance costs. However, this number is relatively low in comparison to the potential number of installations in Cambodia. Progress in biodigester implementation is constrained by a few challenges, such as lacking technical data and technical assessment, limited local and international suppliers active in Cambodia, and substantial knowledge of operation and maintenance in compliance with the standards.

There is a need for biodigester protocols, performance standards, new models, and dissemination methods to enter the biodigester into the market. In this context, strategies on sustainable biodigester development are required to integrate national policy and build national capacity to offer technical, economic, and financial assessment to support the farm owners (MAFF 2016). Recently, multiple government-supported programs provide full-service to the project owners to establish biogas investment (Hyman and Bailis 2018). In 2015, under a GEF project on reducing GHG emission through promoting commercial biogas plants in Cambodia, over USD 1.5 million of funding has been provided to promote investments in biogas-based rural electricity systems, particularly in piggery farms. UNIDO supported financing the incremental costs of demonstration and promotion of commercial biogas plants as a financially viable, reliable, effective, and sustainable mechanism to achieve rural electrification. On promoting investments in a commercial biogas plant, the project works with the private sector to demonstrate biogas projects for cumulative at least 1 MW installed capacity in Cambodia (UNIDO 2020).

Within the context of the GEF project, the Biogas Technology and Information Center Cambodia (BTIC) was established in 2016 under collaboration between UNIDO and RUA to provide technical and financial advice to the potential animal farms and agro-processing factories to engage them in large-scale biogas projects (UNIDO 2015a). The BTIC has a strong network with other biogas centers, researchers, project developers, and suppliers of biogas systems across the region. The center has provided technical training and capacity building related to commercial biogas project development to more than 500 participants from various stakeholders such as pig farmers, project developers and investors, policymakers, financial institutions, researchers, and local engineering companies. It has established a database (<https://btic-rua.org/pages/>) supplier with confirmed biogas suppliers mainly from China and Malaysia, and other countries such as India, Singapore, and Thailand.

The BTIC can estimate biogas production and electricity generation based on the composition of the available feedstocks and the farm's size and estimate investment cost and return on investment. This estimation will help the farm owner decide on the proper system scale and the investment of the commercial biogas plant. The center helps determine the suitable equipment such as gas pipe size and the right generator capacity from suppliers for biogas plant and electricity conversion. The key elements to maximize biodigesters' benefits are to reducing the cost of construction and

improving biodigesters' quality. For instance, by being incorporated with BTIC, M's pig farm can save approximately 24,000 USD a year from biogas investment, and electricity production can meet around 70% of the total annual electricity demand in the farm (UNIDO 2020). With technical and financial support, farm owners and other stakeholders showed their interest in biogas investment. Recently, there has been an increase in the number of biogas projects in farms and factories. In the long run, the BTIC has the mandate to build human and institutional capacity for continuous development and sustainable operation and maintenance of commercial biogas projects. BTIC is also needed to create awareness and develop policymakers, project developers, and financial institutions to promote commercial biogas systems in animal farms. With the knowledge and skills gained to BTIC will serve as a repository center of the nation.

2.5 Potential feedstocks in Cambodia

Commercial biogas systems typically use animal manure as feedstock. Other potential feedstocks from slaughterhouses, agriculture wastes, and wastewaters from agro-industry, such as rubber and cassava, could also be used as substrates for biogas production.

2.5.1 Livestock

Animal production in Cambodia was 40.3 million heads in 2015, and this number rose to 42.2 million heads a year later. The buffaloes, pigs, and poultry production jumped by 41%, 7.1%, and 3.5%, respectively. The family pig production increased to 2.33 million pigs in 2017. As an emerging economic growth and changing of people's habit in eating meat, the livestock production industry is crucial in providing food security for the nation. Some farms switched from conventional to commercial scale. Commercial animal production, particularly pig and chickens, has been noticeably increasing, matching domestic demand and exports. The commercial pig farms were 599,341 heads in 2016 and rose by 30% in 2018 (MAFF 2019). Table 3 lists other commercial farms, and the farm's size is classified by the number of animals, as indicated in Table 4. At least 43 farms were reported as potential farms for biogas production (MAFF 2018). This number will increase as the number of farms keeps rising every year. According to feasibility studies from BTIC, the commercial farms with above 3000 pigs have a high potential for biogas production with a payback period of less than five years. Besides, buffalo farms with more than 1000 heads also have the potential for biogas projects. Estimating biogas production and electricity generation

from different substrates in Cambodia is available on BTIC's website (https://btic-rua.org/pages/cal_bio). However, each farm is unique, and the actual biogas production can vary. The potential biogas production for a specific farm should be determined based on substrates' confirmed availability and properties. The characteristics and analysis of biogas feedstocks will detail in Chapter 3.

In addition, the slaughterhouse waste from those animals also has a great potential for methane production due to the large amounts of solid wastes. Remarkably, most waste from a slaughterhouse has not yet been adequately managed, leading to surrounding environmental pollution. Such slaughterhouse waste management requires great attention from slaughterhouse owners. Within this context, the MAFF imposed three necessary policy measures, which are: 1) Increasing the dissemination of benefits and use of biodigesters to slaughterhouse owners countrywide; 2) Promoting the construction of biodigester in slaughterhouse according to standard set; and 3) Increasing support and incentives to slaughterhouse owners via providing of certificate of appreciation depending to the standard of their applied biodigesters (MAFF 2019). It is a good opportunity for companies that want to invest in biogas production from the slaughterhouse.

Table 3 Commercial farms and their animal production in 2016 (Borany 2016).

Animal types	Number of farms	(Head)
Cattle	93	23,188
Pig	575	599,341
Chicken-meat	320	2,767,466
Chicken-egg	300	1,185,800

Table 4 Classification of the farm size from different animal types (NBP 2019).

Animal types	Small farm (Head)	Medium farm (Head)	Large farm (Head)
Cattle/buffalo-meat	100 – 300	300 – 1,000	>1,000
Cattle/buffalo-milk	20 – 100	100 – 300	>300
Pig fattening (meat)	100 – 1,000	1,000 – 5,000	>5,000
Pig sow (breed)	50 – 200	200 – 500	>500

Goat/sheep/monkey/rabbit	300 – 1,000	1,000 – 5,000	>5,000
Chicken-egg	2,000 – 20,000	20,000 – 50,000	>50,000
Chicken-meat	5,000 – 30,000	30,000 – 50,000	>50,000
Chicken-breed	1,000 – 5,000	5,000 – 20,000	>20,000
Duck	5,000 – 20,000	20,000 – 50,000	>50,000

2.5.2 Agricultural waste

In 2015, agricultural production accounted for 35.6% of Cambodia’s GDP, of which half of it was made up of rice paddy. The main products are rice, rubber, maize, cassava, and sugarcane which amount to approximately 20 million tons (Figure 4). The increase of the production due to the rise of the land area of harvest and the growth of yield, resulting in improved technologies, more irrigation systems, and better access to mechanized services.

The largest concentration of cultivation is around Tonle Sap, the Tonle-Bassac River, the Mekong River, and the provinces of Battambang, Kampong Thom, Kampong Cham, Kandal, Prey Veng, and Svay Rieng, which are rich in fertile and medium fertile soils (Figure 5) (Vang 2015). Rice straw, the rice by-products produced when harvesting paddy, is considered as wastes. Each kg of milled rice produced results in roughly 0.7–1.4 kg of rice straw depending on varieties, cutting height of the stubbles, and moisture content during harvest. Managing rice straw remains a challenge. Rice straw remains typically in the fields after harvest because it is costly to gather up. The widespread burning of rice straw in the field is a major contributor to dangerously high levels of GHG emission and air pollution (Gummert et al. 2020). With the development of recent technologies, rice straw can be processed and managed using better practices. Rice straw bales were compressed in some provinces in Cambodia, such as Svay Rieng, Kampong Thom, and Takeo provinces. The collection of rice straw from the field will help farmers use it for non-energy such as growing mushrooms, mulching for other crops, and bioenergy production such as ethanol, combustion, and biogas production. A range of alternative uses of rice straw will turn into a commodity around and benefit rural people. If market prices of rice straw increase, other areas in Cambodia will make rice straw bales to fulfill the market demand for biogas production.

However, the production of biogas from rice straw feedstock faces some challenges compared to other agriculture wastes. To enhance the fermentation stability of the lignocellulosic biomass, it requires reducing lignin content and cellulosic

crystallinity (inhabitation of degradation of cellulosic) by pretreatments such as NaOH or enzyme using steam explosion method and co-digestion (CSTR unit) (Zhou et al. 2017), in particular, combining agricultural straw with animal manures significantly enhanced methane production (Tsapekos et al. 2017).

2.5.3 Agro-processing industry

In the light of agriculture's technological advancement and integration into production chains and networks of industrial interdependencies, agro-industry and agro-processing industries are considered to improve the quality of agricultural products. There are four main agro-processing industries in Cambodia: rice milling, cassava, sugar, and rubber factory. Commercial rice mill is less than 1000 among the 24,048 mills in 2008 (Pode et al. 2015). Cassava, the second largest agricultural crop after rice, could have substantial social and economic gains if it receives the right level of public commitment and investment. In the second half of 2018, the Cambodian government has officially launched a new strategy for the cassava production and processing industry to produce value-added cassava products, mainly cassava starch, cassava flour, and cassava chips, and export to Vietnam and China. The wastewater from those processing industries contains carbohydrates, proteins, fats, cellulose, and lignocellulose that can convert into biogas through an anaerobic process.

Bagasse waste from sugarcane factories is around 260 kg per ton of cane, and the methane production is approximately 200 m³ per ton of bagasse (Janke et al. 2015). Its low lignin content can be also used as pre-treatment feedstocks with animal manure. On the contrary, wastewater from latex has relatively low methane production in which 1 ton of the concentrated rubber latex can produce about 70 m³ methane (Chaiprapat et al. 2014). These wastewaters are still being laboratory research. Besides, cassava approximately 60,000 L of effluent generate from each ton of cassava tubers process, and the methane production is 15 m³/t_{effluent} (Zeolite and Additives 2020). SOMA energy produces 37,905 m³/day biogas using wastewater from the cassava starch factory in Kam Rieng District, Battambang province.

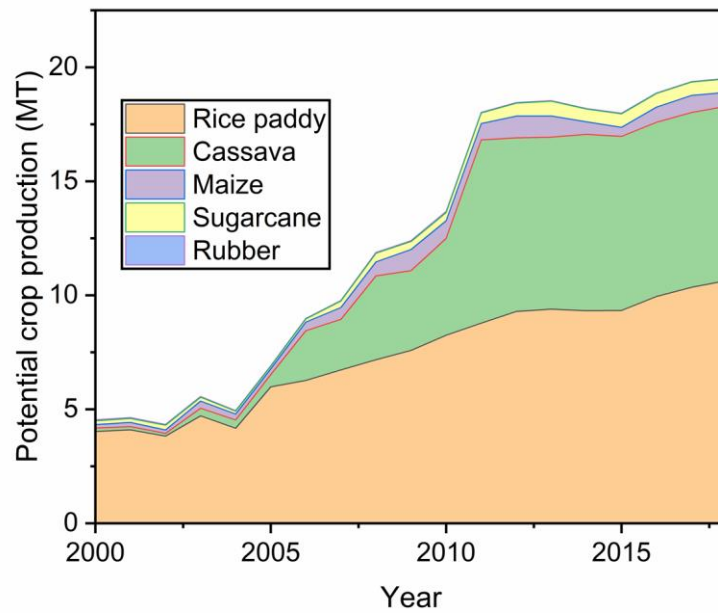


Figure 4 The potential crop production in Cambodia from 2000 to 2018.

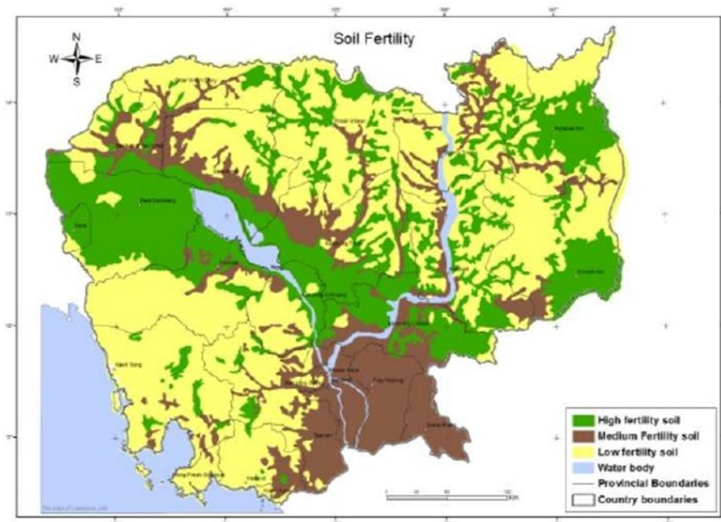


Figure 5 Generalized soil fertility potential map of Cambodia (Vang 2015).

2.6 SWOT analysis for commercial biogas in Cambodia

Table 5 presents a strategic analysis connected with the strengths, weaknesses, opportunities, and threats (SWOT) of commercial biogas under current conditions in Cambodia.

Table 5 SWOT analysis for commercial biogas in Cambodia.

Strengths: - Potential for converting waste to biogas, electricity, and bio-fertilizer - Applicable for a variety of feedstocks: manure, slaughterhouse, and wastewater from agro-industry such as cassava starch, ethanol production, rice flour production - Suitable climatic conditions for biogas production - Low production cost of electricity - Existing biogas plant technology - Available biogas equipment suppliers	Weaknesses: - High investment cost for biogas construction - High O&M cost - Long payback period - Biodigester technology is still limited - Limitation of technology supplier - Competition for biomass (use for other purposes instead of biogas) - Lacking marketable RE technologies/business models - Lack of data from other biogas resources such as municipal waste, slaughterhouse, and other biogas resources
Opportunities: - Growing energy demand - Animal raising is increasing, therefore increase potential farms for biogas production - Policy on biodigester (support from government, GEF, and UNIDO) - Biogas expert from BTIC could help design biogas plant and biogas technology and estimate investment cost and payback period. - Create jobs in the rural areas - Reduce GHG emissions	Threats: - Lacking waste management, for instance, municipal waste and household waste - Lacking the organizational structure to establish an entity or institute of research and development of biodigester. - Lacking institutional and educational capacities - Lacking public awareness for energy efficiency and renewable energies - Loan is not available yet for commercial biogas

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CHAPTER 3: BIOGAS PROCESS AND PRODUCTION

This chapter describes the biochemical process of anaerobic digestion (AD) converting feedstocks to biogas. It is crucial to analyze the composition and quality of the feedstocks to estimate the potential biogas production. Parameters of biogas feedstocks are presented, including their suitability, availability, digestibility, and purity and factors affecting the rate of biogas production. Three main categories of biogas resources will be highlighted, including their merits and limitations. A preliminary feedstock assessment will be given using data available in literature combined with feedstock process and production data to assess the suitability and profitability of biogas feedstocks. The compositions of feedstocks are essential for the Biochemical Methane Potential (BMP). Therefore, laboratory analysis methods for determining TS or DM, VS or ODM, COD, N, C/N ratio, and BMP are discussed in this section.

3.1 Anaerobic digestion

Anaerobic digestion (AD) is the micro-bacterial conversion of organic material in the absence of oxygen. AD is applicable for commercial and pilot anaerobic digestion plant designs using various raw materials, including municipal, agricultural, industrial waste, plant residues, and animal manures (Khalid et al. 2011). AD is a biochemical process involving multiple steps with different groups of microorganisms contributing to the degradation and stabilization of organic materials, leading to biogas (a mixture of CO_2 and CH_4) and microbial biomass (Chen et al. 2008).

Over the last decades, the AD process has been investigated comprehensively for waste/wastewater treatment and renewable energy production in both the industrial and agricultural sectors (Lindmark et al. 2014). The growth and activity of anaerobic microorganisms, i.e., the beating heart of the AD process, and consequently the efficiency of the process is significantly impacted by some main parameters. Therefore, it is crucial to ensure that these parameters are optimized as much as possible. These parameters include constant temperature values favoring microbial growth, pH value, sufficient nutrient supply (substrate composition and C/N ratio), mixing intensity, retention time as well as presence and number of inhibitors (e.g., ammonia and heavy metals) (Seadi et al. 2008).

In anaerobic digestion, organic material is converted to biogas by a series of bacteria groups into methane and carbon dioxide. The majority of commercially

operating digesters are plug flow and complete-mix reactors operating at mesophilic temperatures. The type of digester used varies with the consistency and solids content of the feedstock, with capital investment factors, and with the primary purpose of digestion. The fresh animal manure stores in a collection tank before processing. The homogenization tank is equipped with a mixer to facilitate homogenization of the waste stream. The uniformly mixed waste is passed through a macerator to obtain a uniform particle size of 5-10 mm and pumped into suitable-capacity anaerobic digesters where organic waste stabilizes.

It is vital to know the potential production of biogas for a given feedstock to optimize the AD process. There is a considerable variation in the composition and quality of the feedstocks offered to AD managers and owners, which can be a significant barrier for managers who need to make tremendous efforts to ensure that the installation is fed with feedstock of sufficient quality (Langeveld et al. 2010). The predictability of biogas yield potential based on the quality of feedstocks is essential. Anaerobic bio-gasification potential (ABP) and biomethane potential (BMP) are parameters used to evaluate biogas and methane potential. There is a high correlation between VS and both ABP and BMP (Mayer et al. 2014). ABP is a regression model to predict the potential of biomethane through chemical composition or biological analysis, but it is not widely used (Schievano et al. 2008). BMP defines the yield of CH₄ (per g of VS) of organic substrates in AD (Schievano et al. 2009). BMP is a critical test for the anaerobic degradability and acceptability of a feedstock. Jingura and Kamusoko (2017) summarized the available methods, both experimental and theoretical or novel approaches to determine the BMP and ascertain the effectiveness of the AD process and the biodegradability of organic substrates. These methods use the same principle, but the technical approaches and experimental setups may be different. The BMP test has several variants. Several trials have defined a standard protocol for the ultimate BMP test to achieve comparable results. Despite the wide use of the BMP test, no commonly accepted experimental procedure yet exists. AD is a complex and dynamic system that closely relates microbiological, biochemical, and physicochemical characteristics (Angelidaki et al. 2009). However, three commonly used methods including the German standard procedure, Verein Deutscher Ingenieure (VDI 4630), and the Møller and the Hansen methods (Pham et al. 2013).

3.2 Biogas feedstocks

The substrates used in practice for biogas production are selected based on their suitability and availability. The suitability of feedstocks for biogas production is defined from several characteristics and parameters such as the content of easily digestible organic matter, methane potential, particle size, dry matter content, pH, C:N ratio, and macro-and microelements, etc. Availability means that the feedstock is easily accessible for biogas plant operators with sufficient amounts regularly (Drosg et al. 2013).

3.2.1 Overview of biogas resource

Significant sources of biogas feedstocks are agricultural (animal manures and slurries, vegetable by-products and residues, energy crops), industrial (organic wastes, by-products, and residues from agro-industries, food industries, fodder, and brewery industries, organic-loaded wastewaters and sludges from industrial processes, organic by-products from biofuel production and biorefineries, etc.), and municipal (source-separated household waste, sewage sludge, municipal solid waste, and food residues) operations (Langeveld and Peterson 2018).

A variety of organic feedstocks consisting of animal manure, municipal waste, and agro-industrial waste has a significant variation in the composition and quality of the feedstocks offered to AD (Langeveld et al. 2010). Other compositional elements may seriously limit their potential biogas production. As aforementioned, yield expresses as biogas or pure methane (CH_4), produced per VS, TS, or fresh matter (FM) unit. Thus, the TS and VS values are crucial data accompanying biogas yield data for accurate conversion and comparison with their literature values. Table 6 presents the classification of the biogas plant. The values indicate that biogas yields can be high or low, depending on the composition of the solids (Langeveld and Peterson 2018). However, the biogas yield varies from region and country, especially from animal manure and agriculture residue. Three major biogas yield categories per ton of VS can be distinguished: low: $<300 \text{ m}^3$ (lignocellulose, cattle, and pig manures); modest: $300\text{--}500 \text{ m}^3$ (chicken manure, MSW, and banana stalks); and high: $>500 \text{ m}^3$ (abattoir effluents and potato starch effluents) (Langeveld and Peterson 2018).

Table 6 Biogas and methane production potential for different AD feedstocks (Langeveld and Peterson 2018).

Liquid feedstocks	m ³ CH ₄ /ton VS	m ³ CH ₄ /ton TS	m ³ CH ₄ /m ³ effluent
Potato effluent	611	550	22
Pome	562	483	15
Abattoir wastewater	700	560	84
Cattle slurry	234*	192*	21*
Pig slurry	201*	181*	13*
Solid feedstocks	m ³ CH ₄ /ton VS	m ³ CH ₄ /ton TS	m ³ CH ₄ /m ³ effluent
Food residues	260	239	48
Chicken manure	309*	252*	101*
Cattle manure	236*	180*	45*
MSW	386*	348*	70*
Lignocellulosic Feedstocks	m ³ CH ₄ /ton VS	m ³ CH ₄ /ton TS	m ³ CH ₄ / m ³ effluent
Bagasse	122	119	112
Pre-treated bagasse (NaOH)	177	172	162
Forest residues	214	137	103
Pre-treated forest residues	266	170	128
Banana stalks	347	13	0.1
Banana stalks (sundried)	236	196	180
Coffee pulp	131	119	66
Pre-treated coffee pulp (NaOH)	174	158	88
Wheat straw	282	265	260
Corn stover	296	288	268
Maize silage	259	396*	139*
Grass silage	344–383	330*	180*

*Methane estimated as 60% of reported biogas yield values

Types of biogas feedstocks

(a) Agriculture waste

Biomass resources suitable as biogas feedstock include various organic materials originating from agriculture, such as crop residues like stalks, leaves, husks, cobs, and industrial and municipal residues and wastes. Biomass is the general term used to describe all biologically produced matter and therefore includes all kinds of materials and substances derived from living organisms. Agricultural lands occupy 37% of the earth's surface, accounting for 52% and 84% of global anthropogenic methane and nitrous oxide emissions. Apart from this, animal farming accounts for 18% of worldwide GHG emissions. Most of these emissions originate from the 13 billion tons of animal manure and slurries estimated to produce annually worldwide. Many agricultural practices such as water and rice management, set-aside, land-use change and agroforestry, livestock management, and manure management for biogas feedstocks can potentially mitigate GHG emissions (Smith et al. 2008). Agricultural wastes for AD feedstocks have also been associated with the treatment of animal manure and slurries and the stabilization treatment of sewage sludge from wastewater plants (Biosantech et al. 2013).

Animal manure is one of the most common substrates for biogas production in the AD process, even though only a tiny fraction of the global production is currently digested in biogas installations. The global forecast for manure availability is some 28 billion tons by 2050, of which an estimated 50% can be recovered. Manure is a mixture of feces and urine, and its chemical composition varies markedly depending on the species of origin and the quality of the animal feed. Animal manure comprises huge amounts of lignocelluloses, polysaccharides, proteins, and other biomaterials (Jingura and Kamusoko 2017). Dry matter or total solid contents of solid farmyard manure is 10–30%, and the liquid slurry is below 10%. Manures and slurries from pigs, cattle, poultry, horses, and many others can be used as substrates for biogas production. Cow and pig manures are promising feedstocks for AD as they are rich in various nutrients necessary for the growth of anaerobic microorganisms. They also have a high buffer capacity which can stabilize the AD process in a significant pH decrease inside the digester.

(b) Municipal waste

Municipal wastes refer to the source-separated household waste, sewage sludge,

municipal solid waste (MSW), food residues, garden waste, and other similar organic wastes. The organic fraction of MSW is biodegradable and defines as organic waste or biowaste. In many cases, MSW is usually brought to landfills; therefore, an increasing effort is made to valorize this potentially valuable feedstock for high-quality compost and biogas chains. In the anaerobic stages of MSW, retention time is more than 15 days at 35 °C (Deublein and Steinhauser 2011). In Europe, biowaste is shifted away from landfills, leading to the selection of biogas production, which estimated the digestion of 3–4% of EU biowaste. Food processing waste varies between 250 and 800 kg per ton of raw food, and biodegradable urban waste can be as high as 70 kg per person per year. Worldwide, 6 billion tons of urban waste are expected to be produced each year by 2025. As some 1 billion tons of this will be biodegradable, the biogas production potential amounts to 86 million average cubic meters (Nm³) with an equivalent energy content of 1.8 Exajoule (EJ) (Langeveld et al. 2016). Increasingly high amounts of household wastes generated in society indicate a very high AD potential. Organic household wastes have a high biodegradability and methane yield, and their nutrient content is well balanced and favorable for the metabolism of anaerobic microorganisms (Zhang et al. 2007).

(c) Industrial waste

Massive amounts of organic wastes, by-products, and residues are produced in agro-industries, food industries, fodder, and brewery industries, including organic by-products and organic-loaded wastewaters sludges from biorefineries that need to be treated or disposed of. These organic wastes can use a wide range of organic feedstocks for AD such as pomace from winemaking, animal feed, breweries, sugar refineries, and fruits processing plants, or even the wastewater from dairies or waste from slaughterhouses can be used for the production of bioenergy (Deublein and Steinhauser 2011). In grain-processing bio-ethanol industries, all silage fractions become more prominent for integrating the industrial AD process. Worldwide bio-ethanol production was about 95 million m³ in 2010. One significant drawback is that high volumes of bio-ethanol produce high amounts of effluents. These large quantities will demand proper strategies for using and treating the anaerobic digestion effluent (Drosg et al. 2013).

Barrier of feedstocks

Biogas from agricultural substrates contributes likewise only little to the energy system. The agricultural sector observed the trend and accepted it conditionally since the biogas facilities did not work profitably, mainly because of the high construction costs. The facilities ran economically only after the farmers had learned to work themselves and pool their experience (Deublein and Steinhauser 2011). Animal slurries have a low DM content (3–5% for pig slurries and 6–9% for cattle slurries). They will give a low methane yield per unit volume of digested feedstock, ranging between 10 and 20 m³ methane per cubic meter of digested slurry, while biomass transport costs are high (Angelikaki and Ahring 2000).

On the other hand, the main limitation of using municipal wastes and organic wastes for biogas production is their potential content of undesirable matter such as biological, physical, or even chemical pollutants. For example, household waste contains various pathogens, fungi, and other contamination substances (chemical and biological). In contrast, industrial wastes contain physical impurities, pathogens, heavy metals, or persistent organic compounds in such amounts that they could become sources of environmental pollution or pose health risks for humans and animals when the produced digestate uses as fertilizer. The required content of foreign materials may not exceed 0.1% to prevent a negative impact on the utilization of digestate as fertilizer. Therefore, specific materials, such as food residues, MSW, household, and slaughterhouse, must be sanitized to react to the pathogenic matter prior to AD effectively. The method to separate the collection of organic matter from those residues is relatively high cost. Another critical limitation is a shortage of organic waste, especially methane boosters, in countries with well-developed biogas markets. Industrial organic wastes will likely continue to use when available because of their high methane yields, especially as co-substrates for animal manure. The environmental benefits of AD and the high costs of other disposal methods are further incentives in favor of using suitable industrial organic wastes, by-products, and residues as biogas feedstocks (Biosantech et al. 2013).

3.3 Characteristics and Analysis of biogas feedstocks

The digestion type and size selections are based on the substrate's characterization to be treated, the investment capital required, the target outcome power, etc. Besides, feedstock selection should also consider optimizing other aspects

of performance, such as digestate quality and biogas production (Banks and Ven 2013). It is essential to know that some feedstocks are difficult or unsuitable for producing biogas because of their unfavorable C/N ratios or high lipid content. Different feedstocks may have to be blended or pretreated to obtain a composition suitable for biogas production. For instance, a mixture of slaughterhouse wastes with animal slurries or MSW (Alvarez and Lidén 2008) or the treatment or digestion of livestock manures with cheese whey (Kavacik and Topaloglu 2010) or glycerol (Astals et al. 2011) can resolve any imbalances and improve the volume of methane productivity. Therefore, the proper characterization of feedstocks' physical and chemical composition can determine feedstock selection for biogas production.

3.3.1 Preparation of sampling

The quality of feedstocks can differ depending on the time and sampling location. The sample taker's experience and knowledge of the overall process of taking, transporting, and storing sampling are essential. According to VDI 4630, to obtain the best results, the rationale for and methodology of selection needs to be clarified in advance, to include the aim of investigation, type of feedstocks, expected sample characteristic, variation of sample characteristics with time and location of sample taking, and parameter to be analyzed. Details on biogas feedstocks' sampling are generally described in standard VDI 4630, and the selection of sludges and wastewater is defined in ISO 5667-13.

A representative sampling procedure is essential for obtaining accurate data or minor errors, as many substrates have inhomogeneous consistency. Generally, physical impurities can be sorted out from the sample, but their amount and mass must be documented. Samples can be dried before an analysis but are suitable when non-volatile substances are being measured. It can cause the loss of some volatile components and, therefore, a false result. For homogeneous material, one sample is generally sufficient for a representative analysis, whereas for material with inhomogeneous phases, at least one sample should be drawn from every step. If the material is very inhomogeneous and no stages can be located, samples should be drawn either from different locations and depths of the material or from mixed material. The liquid material requires an additional stirring process, store in the bottle, and submerge into the liquid for sampling well before sampling. If a sampling valve is used, the first material leaving the valve should be rejected to allow cleaning of the sampling valve. If a sample is taken from a

pipe where the material passes at different flow rates and compositions, a sample proportional to flow rate or volume can be taken. In addition, sampling in a pipe is preferably carried out in a vertical pipe or a pipe with a turbulent flow to avoid problematic sediments (Drosg et al. 2013).

After sampling, clean re-sealable sampling vials made of inert plastic, glass, or steel should be used, and the vials must be labeled. If poor biologic stability of the sample is assumed, samples must be cooled to 4 °C during transport. All samplings should be stored in a cooling chamber at 4 °C until analysis. Obviously, short storage times before analysis are preferable to long storage times. If longer storage times are expected, samples can also be stored at 20 °C, although this might produce changes in the degradability of the substrate.

3.3.2 Laboratory analysis of feedstocks

The characteristics and compositions of the feedstock affect the configuration, design, and operational parameters of an anaerobic digester. The feedstock also determines the quality and quantity of biogas and digestate produced and therefore directly impacts the overall economy of the biogas plant. The composition of the feedstock that is to be digested is one of the essential elements in determining the size of the digester and thus the investment cost of the plant, as longer retention times require a larger digester volume. The feedstock supplied determines to a large extent the main objective of the AD treatment. A laboratory analysis is done to determine the biophysical characteristics, and a BMP assay is used to measure anaerobic biogas production. The biophysical characteristics involve analysis of TS or DM, VS, organic dry mass (ODM), chemical oxygen demand (COD), nitrogen content, and carbon/nitrogen ratios.

(a) Total solids (TS) and volatile solid (VS)

TS and VS tests are conducted to determine the percentages of dried solids content and organic dried solids content in the substrates. These percentage values are important to decide on the quantity of the substrates required in the BMP Test. TS is the amount of solid remaining after heating the feedstock sample so that water is allowed to evaporate. The amount of sample typically required is only 0.25–1 g for solid samples, 1–2.5 g for slurry samples, and 5 mL for liquid samples. It should be filtered using a 0.2 µm pore size filter before TS analysis (Mahmoodi et al. 2018). If feedstocks have high TS content, adding freshwater or other liquid feedstocks to the

biogas plant is necessary and vice versa for a low TS content of feedstocks. However, this method has a drawback for wastewater and industrial by-products wastes because such volatile acids and alcohols substances, which represent a considerable percentage of the energy in the feedstocks, cannot be determined. For the TS test, samples at least in triple are dried in a vacuum oven at (105 ± 5) °C for at least 4 h until obtaining constant weight at according to standards SS-EN 12880-20f00 (Murphy and Thamsiroj 2013). The constant mass is reached when, during the drying process, the difference between two successive weighings of the sample, first heated, then cooled to room temperature and with an interval of 1 h between them, does not exceed 0.5 % (m/m) of the last determined mass. The masses before and after the drying process are used to calculate the dry residue and the water content. The average TS percentage of the feedstock is calculated in Equation 1.

$$\%TS = \frac{\text{Dried weight}}{\text{Wet weight}} \times 100\% \quad (1)$$

In many cases, it will be sufficient to determine the VS to estimate the energy content. The 105 °C-dried sample is burned into the constant weight in a furnace at 550 °C for at least 2 h until the constant mass is achieved (Tabatabaei et al. 2018). The ash was kept in a desiccator to prevent moisture absorption and weighed. The percentage of VS is calculated in Equation 2.

$$\%VS = \frac{\text{Dried weight} - \text{Ash weight}}{\text{Dried weight}} \times 100\% \quad (2)$$

Although this is a valuable and straightforward analysis, it is important to note that the amount of organic matter in a sample does not directly give sufficient information on the anaerobic degradability of the feedstock. As aforementioned, some volatile substances might leave the sample during the first drying at (105 ± 5) °C.

(b) Chemical oxygen demand

A chemically oxidizable material is determined by measuring the COD of a feedstock. COD represents the maximum chemical energy present in the feedstock. Since microbes convert chemical energy to methane, this is also the maximum energy recovered as biogas. However, losses for the energy demand of the microbes themselves have to be subtracted and for material that is not degradable by anaerobic

microorganisms (e.g., lignocellulosic material). This amount of energy is thus the absolute maximum of energy that could be recovered by biogas. However, under chemical conditions, some substances can be oxidized that are not accessible under biological conditions and will therefore remain in the digestate. Using continuous fermentation trials, the residual COD in the effluent of a stable process can be measured, and consequently, the exact COD degradation is determined. In this analysis, the sample is refluxed in a boiling mixture of sulfuric acid and a known excess of potassium dichromate ($K_2Cr_2O_7$). A silver sulfate catalyst can be added for improved oxidation performance. Apart from that, mercury nitrate can be added to counteract the interference of chloride ions by forming complexes with them. In the next step, the remaining unreduced potassium dichromate is titrated with ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2$), which allows the determination of the consumed oxygen equivalents according to Standards DIN 38 414. COD can be calculated in Equation 3.

$$mg.L^{-1}COD = \frac{[(A - B)C \times 8000] - 50D}{mL \text{ of sample}} \times 1.2 \quad (3)$$

Where A and B (in mL) are $Fe(NH_4)_2(SO_4)_2$ for blank and sample, respectively; C is the normality of $Fe(NH_4)_2(SO_4)_2$; D is chloride correction, and 1.2 is compensation factor to account for the extend of chloride oxidation which is dissimilar in systems containing organic and non-organic material. However, this method can give relatively high errors due to sample inhomogeneity and the many sample treatment steps required (dilution, weighing, and titration). For biogas feedstocks containing high concentrated OM and bulky material, drying and milling of samples can improve reproducibility. It is also important to be aware of the toxic components (potassium dichromate, mercury nitrate) used in COD measurements and their proper disposal.

(c) Nitrogen content

Nitrogen is essential for protein synthesis and is primarily required as a nutrient by the microorganisms in anaerobic digestion. The nitrogen content of a feedstock can be determined by the Total Kjeldahl Nitrogen (TKN) determination. TKN in a sample is used to evaluate the nitrogen available for the growth of anaerobic bacteria. In this analysis, organic nitrogen is converted to ammonia and nitrogen by boiling the feedstock sample in sulfuric acid and a catalyst. A base is added, and ammonia is

distilled from the alkaline solution to an acid solution where ammonia is absorbed quantitatively (Drosg et al. 2013). The amount of ammonia can be determined by potentiometric acid titration or the photometric phenate method (ISO 5663 and 11261). In the form of ammonium, nitrogen contributes to stabilizing the pH value in the bioreactor during the process, and microorganisms assimilate ammonium to produce new cell mass.

In most cases, there will be excessive nitrogen in the biogas reactor, and it can be assumed that 60–80% of the TKN will be degraded to ammonia during AD. Ammonia in high concentration in digester will lead to the inhibition of the biological and methanogenesis process (Khalid et al. 2011). Sterling et al. (2001) found that the amount of ammonia in the digester may also affect the production of hydrogen and the removal of volatile solids. Total biogas production was unaffected by slight increases in ammonia nitrogen, while higher increases reduced biogas production by 50% of the original rate.

3.3.3 Biochemical methane potential

Biochemical methane potential tests are mainly used to determine the possible methane yield of a feedstock. These tests also provide information on the anaerobic degradability of a feedstock, including the degradation rate. Numerous alternative options have been proposed to estimate the BMP of organic substrates (Hansen et al. 2004). The methods use the same principle, but the technical approaches and experimental setups may differ (Rodriguez 2011). Most experimental techniques are batch methods. Jingura and Kamusoko (2017) reported the number of practical ways with various feedstocks to estimate BMP. They stated that the BMP values affect by the factors of raw material composition, total and volatile solids, chemical and biological oxygen demand, C/N ratio, inhibitory substances, and agronomic practices.

On the other hand, novel approaches to determine BMP are required since the current protocols are expensive and time-wasting (Triolo et al. 2011). As such, cost and time are critical parameters in the choice of method. The experimental set-up of the simplified BMP test was reported by (Drosg et al. 2013). The expensive eudiometer gas measuring devices are replaced by simple water displacement bottles, making the test more practical. In addition, a bottle with an alkaline solution is placed after the digester vessel to absorb the produced carbon dioxide and allow direct methane measurement.

3.4 Component affecting biogas production

The anaerobic digestion of organic material is a complex process involving many different degradation steps. The micro-organisms that participate in the process may be specific for each degradation step and thus have additional environmental requirements. Certain primary conditions such as the absence of oxygen (anaerobic conditions), uniform temperature, optimum nutrient supply, and optimum and constant pH must be met to enable the bacteria to degrade the substrate efficiently (Gomez and Costa 2013). Besides, feedstocks for biogas production vary significantly in terms of composition, digestibility, methane potential, dry matter content, the content of nutrients, and other characteristics. The methods of biogas production can fully understand the correlation between a given feedstock and its potential biogas yield, the number of process steps, the process temperature, pH, and physicochemical properties, including moisture content and available organic materials, which are necessary to describe them. The description, advantages, and disadvantages of each method were summarized by (Ghodrat et al. 2018), and the characterization standards were listed by (Drosg et al. 2013). Most AD processes run optimally at neutral pH and a C:N ratio of the substrate mixture between 20:1 and 30:1. The anaerobic microorganisms inside the digester need to supply some basic ingredients necessary for their metabolism. Therefore, mixing more than one feedstock (co-digestion) is common to obtain a balanced substrate composition and a synergic effect of improved process stability and higher methane yield (Biosantech et al. 2013).

3.4.1 Temperature and pH

Temperature has a significant effect on the microbial community, process kinetics and stability, and methane yield. Lower temperature decreases microbial growth, substrate utilization rates, and biogas production during the process, resulting in cell energy exhaustion, leakage of intracellular substances, or complete lysis. On the contrary, high-temperature results in lower biogas yield due to ammonia's volatile gases, suppressing methanogenic activities (Khalid et al. 2011).

AD occurs under two main temperature ranges, which are mesophilic (25–40 °C) and thermophilic conditions (45–65 °C). A temperature range between 35–37 °C is considered suitable for methane production under mesophilic conditions (Moset et al. 2015). Castillo et al. (2006) indicated that the best operational temperature of mesophilic and thermophilic was 35 °C and 55 °C, with the retention time range from

15 to 30 days and 12 to 14 days, respectively. The optimum digestion temperature may vary depending on feedstock composition and the type of digester. In most AD processes, it should be maintained relatively constant to sustain the gas production rate. A constant temperature is required for optimized process stability and efficient biogas plant operation, as shocks and fluctuations can disturb the performance and changes in the microbial community structure. Most AD plants operate at mesophilic temperatures. Their operating range is more stable, requires less energy for heating, and has a broader range of activity and lower risk of ammonia inhibition and process failure than the thermophilic process. However, thermophilic digesters are more efficient in retention time, loading rate, and nominally gas production (Gao et al. 2011).

The pH value determines the acidity or basicity of an aqueous solution. The pH value can be measured in a liquid feedstock with a standard potentiometric electrode (standards EN 12176). In semi-solid or solid feedstocks, the sample can be mixed with water and then analyzed. The optimal pH ranges of the hydrolysis and acidogenesis stages are 5.0–6.0 and 5.5–6.5, respectively, whereas the ideal pH range for methanogenic bacteria is 6.8–7.2 (Ward et al. 2008). Similarly, a narrow range of suitable pH values has been found between 6.5 and 7.5 to attain maximal biogas yield in AD (Liu et al. 2008). The pH value in anaerobic fermentation is usually above neutral. The buffer capacity depends on CO₂ concentration in the gas phase, the ammonia concentration in the liquid phase, and water content. It is preferable to have a neutralization step before feeding to the biogas plant. If slight acidification occurs during AD, the pH can be increased by adding a base, for instance, Ca(OH)₂, Na₂CO₃, or NaOH, in the reactor (Drosg et al. 2013; (Ghanavati 2018).

3.4.2 Moisture

High moisture contents usually facilitate the AD process and likely affect the process performance by dissolving readily degradable organic matter. The high yield of methane production occurs at 60–80% of humidity (Bouallagui et al. 2003). However, it is difficult to maintain the same water availability throughout the digestion cycle because the water added at a high rate is initially dropped to a lower level as anaerobic digestion proceeds. Hernández-Berriel et al. (2008) studied methanogenesis processes at 70% and 80% moisture levels during anaerobic digestion. They found that bioreactors at similar ratios of biochemical oxygen demand (BOD) to chemical oxygen demand (COD), AD under the 70% moisture regime produced stronger leachate and a higher methane production rate. 83 mL methane per gram dry matter was produced at

the 70% moisture level, while 71 mL methane was made with 80% moisture.

Besides, the rate of AD is strongly affected by the substrate's type, availability, and complexity (Ghaniyari-Benis et al. 2009). Before starting a digestion process, the composition of the substrate, such as carbohydrate, lipid, protein, and fiber contents, should be characterized for the quantity of methane that can potentially produce under AD conditions (Lesteur et al. 2010). The initial concentration, total solid content, chemical and biological demand, and carbon/nitrogen (C/N) ratio of the substrate in the digester can significantly affect the performance of the process and the amount of methane produced during the process (Fernández et al. 2008).

3.4.3 Raw material composition

Methane yield varies for different chemical constituents or the same biomass feedstock (Mayer et al. 2014). Weiland (2010) indicates that fats and proteins produce more methane than carbohydrates and lignin, which are not biodegradable under AD (Table 7).

Table 7 Maximum gas yields and theoretical methane contents (Weiland 2010).

Substrate	Biogas (Nm ³ t ⁻¹ TS)	CH ₄ (%)	CO ₂ (%)
Raw fat	1200 – 1250	67 – 68	32 – 33
Carbohydrates	790 – 800	50	50
Raw protein	700	70 – 71	29 – 30

3.4.4 Total solids and volatile solids

Total solids (TS) indicate an organic and inorganic portion of matter. The TS content of the feedstock is analyzed by drying the sample to constant weight in a drying chamber at 105 °C. TS content of feedstock influences AD performance, especially biogas production efficiency. Systems used in AD are classified according to the percentage of TS in the feedstock. Three main types of AD technologies that work according to the TS content of feedstocks are ≤10%, 10–20%, and ≥20% TS for conventional wet, semi-dry, and modern dry processes, respectively (Yi et al. 2014). Total methane yield decreases typically with an increase of TS contents from 10% to 25% in batch AD under mesophilic conditions (Abbassi-Guendouz et al. 2012). There is evidence that biomethane yield is also affected by VS content; therefore, BMP can

be predicted with reasonable accuracy using solely the VS content (Schievano et al. 2009).

3.4.5 Chemical and biological demand

Chemical oxygen demand (COD) quantifies the amount of organic matter (OM) in feedstocks. COD is a parameter that indicates the total chemically oxidizable material in the sample and represents the maximum chemical energy present in the feedstock. Since microbes convert chemical energy to methane, biogas can be calculated. Theoretical CH₄ production is 0.35–0.5 Nm³/kg COD removal; thus, biogas production will be higher as CH₄ is only part of the biogas (Angelidaki et al. 2009). Biological oxygen demand (BOD) measures oxygen used by microorganisms to decompose OM. Typical BOD values are: pig slurry 20,000–30,000, cattle slurry 10,000–20,000, and wastewater 1,000–5,000 mg L⁻¹ (Korres et al. 2013).

Chemically oxidizable material can be determined by measuring the COD content of a feedstock. This amount of energy is the absolute maximum of energy that could be recovered by biogas. However, some substances can be oxidized under chemical conditions, but they are not accessible under biological conditions and remain in the digestate. Using continuous fermentation trials, the residual COD in the effluent of a stable process can be measured, and consequently, the exact COD degradation can be determined. The relationship between BOD and COD varies among types of wastewaters from the activities of industries. Wastewater contains a higher level of oxidizable chemical substances than biodegradable organic matter. The biodegradable index or biodegradation capacity (BOD/COD ratio) is typically 0.3:0.8 and 0.5:1 for untreated municipal and raw domestic wastewaters, respectively (Al-Sulaiman and Khudair 2013).

3.4.6 Carbon/nitrogen ratio

There is an interactive effect between temperature and C/N on AD performance. The C/N ratio represents the relationship between nitrogen and carbon in a feedstock (Wang et al. 2014). A low ratio means that the material is protein-rich. AD of such material results in increased free ammonia content that causes high pH leading to methanogenic inhibition (Khalid et al. 2011). Therefore, a higher C/N ratio would be required to reduce the risk of ammonia inhibition when the temperature is increased. However, a high ratio causes rapid depletion of nitrogen needed for the reproduction of the bacteria, causing lower gas production. A comparable range of C/N ratios for waste

digestion 10:1 to 45:1 for the hydrolysis step and 20:1 to 30:1 for the methanogenesis step (Drosg et al. 2013). (Dioha et al. 2013) gave typical C/N ratios for some feedstocks: cattle manure 13:1, chicken manure 15:1, grass silage 25:1, rice husks 47:1, while 25:1 is a broad practice value.

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CHAPTER 4 BIOGAS PLANNING, DESIGN, AND TECHNOLOGY

The planning, design, and technology selection of a biogas plant must be made to ensure the economic operation of the biogas plant with the available feedstock. The planning includes pre-feasibility and feasibility studies that aim to estimate the feedstocks available for biogas production, energy, investment costs, and the economics of a biogas project. The biogas plant design includes determining the reactor type and volume and the capacity of biogas utilization systems. The last section presents lagoon technology already used for biogas production at a commercial scale in Cambodia.

4.1 Basic steps in the planning of a biogas plant

Farmers and farmers' organizations, organic waste producers and collectors, municipalities, and other stakeholders are the usual initiators of biogas projects. From the vital spark of a biogas project idea to the end of its lifetime, the process generally undergoes the following steps: (1) Project idea; (2) Pre-feasibility study; (3) Feasibility study; (4) Detailed planning of the biogas plant; (5) Permission procedure; (6) Construction of the biogas plant; (7) Operation and maintenance; (8) Re-investment and replacement; and (9) Demolition or refurbishment (Seadi et al. 2008). The process starts with the project idea and the first pre-feasibility to estimate the biogas production. For this purpose, online biogas calculators can be used from BTIC's website (<http://btic-rua.org/pages/service#>). The reports of preliminary planning summing up all boundary conditions like technical aspects and investment budget should be handed out to potential financiers like banks, institutional investors, private persons, or groups of private persons (Seadi et al. 2008).

There are different successful models of setting up a biogas project, depending on the feedstock availability, options for biogas utilization, and the financial capability of the investors. If the project initiator and the investor arrive at the point of decision making, an experienced biogas consulting company or institution could be involved. The biogas consultant helps the farm owners and investors to estimate the biogas amount and select the technology (wet or dry digestion, process temperature, type of digesters, size of the digester, types of biogas utilization CHP generation, biogas upgrading, and electricity generation), and estimate the detailed cost budget for the investment and operation of the plant (cost of individual components, labor costs,

maintenance and repair, interest from bank, financing/permitting, and planning/engineering costs (Gupta 2020).

4.1.1 Feasibility study

Most farms are unique, so consulting with a biogas expert for a field visit is essential to ensure a proper biogas system design. The feasibility study is to create an economically profitable model for a biogas plant investment. The typical data for a range of, for instance, animal farms such as the number of livestock, manure per day, DM, and the data from laboratory analysis of feedstocks allows the biogas expert to estimate the biogas production and electricity generation (Langeveld and Peterson 2018). Based on the amount of potential feedstock to be used in the biodigester, the selection of technology, and the biogas utilization, the dimension and size of the biogas plant can be designed and constructed. Finally, the economics of the biogas plant is analyzed based on the investment costs, the operating costs, and the financial benefits. The planning process for constructing a biogas plant is complex and time-consuming. Before, during, and after the construction, a wide range of financial, economic, environmental, and social issues need to be considered (more detail in Chapter 7).

4.2 Design of biogas plant

For designing an anaerobic digestion plant, it is important to accurately establish the technology to be used and the volume required for digestion. Every biogas plant design should start from the selection and analysis of the feedstocks available. The knowledge needed on the substrate should not be limited to the time of analyzing the project but should also consider future changes. The best scenario is to have a complete picture of the situation faced by acquiring and the following data: (i) available quantity of feedstocks per day, per year and receiving frequency; (ii) quality of the feedstocks in terms of TS, VS, and other substances; and (iii) suggested HRT, OLR, and temperature of digestion (Ghodrat et al. 2018). The calculation of the volume is generally performed after deciding on the other configurations and operating conditions of the plant, mainly (1) available feedstocks, quantity, and characteristics (wet or dry digestion); (2) process conditions (temperature of digestion, for instance, mesophilic or thermophilic); (3) reactor control or volume; and (4) technology (from a batch process to continuous process, for instance, plug-flow, CSTR, USAB, lagoon, etc.). The first two parameters have been described in Chapter 3. This section presents the reactor volume by determining the value of HRT and OLR and types of co-digestion. Also, the

possibility of co-digestion should be considered, as this can lead to increased biogas production scale.

4.3 Reactor volume

The total digestion volume is defined by the hydraulic retention time (HRT) or the organic loading rate (OLR). The reactor volume generally needs to be adapted to the amount of feedstock, the critical substrates' degradation rate, and the anaerobic bacteria's propagation speed. Micro-organisms must have sufficient time for the degradation process, which sets a particular minimum retention time. The concentration of organic matter must not be of a level that leads to overfeeding the microbes and thus processes inhibition, which sets a certain maximum OLR. The HRT and OLR are used to calculate the digester volume (Sarker et al. 2019).

4.3.1 Hydraulic retention time

Retention time is an important parameter used for the design and optimization of anaerobic digestion. The retention times of given feedstocks depend on the digestion temperature and eventually on the pre-treatment (Talia 2018). It mainly depends on the type of reactor to be used and the type of substrate. Retention time refers to HRT and solid retention time (SRT). HRT represents the retention time of the liquid phase, whereas SRT denotes the retention of the microbial culture in the digester. In an anaerobic reactor system where the feedstock (food waste, kitchen waste, and MSW) and mixed microbial cultures are present at the same phase, the HRT is essentially SRT and vice-versa. In contrast, for substrates like waste-activated sludge and primary sludge, the interaction between solids and microbial cultures is biphasic, making HRT and SRT different (Sarker et al. 2019). Sludge blanket and anaerobic film reactors, suitable for low-strength waste waters, typically have a low HRT and high SRT.

The HRT describes the theoretical time the substrates stay in the digester, and the mean retention time deviates from this value. The HRT is a statistical and calculative value from the active volume of the biogas plant and the volume of added substrate per day, as shown in Equation 3 (Rosato 2018).

$$HRT \text{ (days)} = \frac{\text{Net digester volume (m}^3\text{)}}{\text{Substrate input (m}^3\text{/day)}} \quad (3)$$

The selection of HRT value must allow adequate substrate degradation without increasing the digester volume too much. Washout of the microbes must be avoided;

therefore, the HRT must not be below 10 days (Gomez and Costa 2013). The choice of HRT differs based on feedstock composition, processes, and temperature. The HRT on the methanogenesis is related to the operating temperature. Biogas and methane production in thermophilic conditions have higher production rates than in mesophilic states. Kim et al. (2006) indicated that the HRT ranged from 8 to 12 days with temperature between 30 °C to 55 °C. Substrates rich in starch and sugar can be easily digested, resulting in shorter retention times. Still, fiber and cellulose plant matters like corn stalk and rice straw require longer retention times as hydrolysis of these substrates occurs at a slow rate. However, shorter HRT risks bacterial mobilization, including the build-up of higher molecular weight VFAs (volatile fatty acids) and consequently elevated stress to the methanogens.

Conversely, a longer HRT increases the digester size; therefore, the optimal operational HRT is usually neither too long nor too short. In the case of different AD phases, a longer HRT is typically preferred for methanogenesis to match the slower growth rate of methanogens compared to acidogenesis. Some digesters are designed in a multi-stage so that acidogenesis and methanogenesis can be separated into two different volumes, allowing each group of microorganisms to operate at the optimal conditions (Sarker et al. 2019). The optimization strategy for the digester might need to increase the VS content of the substrate (very low slurry) by dewatering until reaching the limit value for the HRT (Banks and Ven 2013).

4.3.2 Organic loading rate

The organic loading rate (OLR) is the amount of organic matter added to an AD system per day per unit of reactor volume. OLR is a measure of the biological conversion capacity of the AD system. Its value is estimated based on the different biological parameters and represents the loading stress value of the digester. It is possible to increase the OLR if the substrate is easy to digest by the microbial populations and the conditions for digestion are optimal. At the same time, it should be kept at a lower level if the digestion process of recalcitrant substrates is intended (Talia 2018). OLR is a crucial control parameter in continuous systems. Many plants have reported system failure due to overloading.

Feeding the system above its sustainable OLR results in low biogas yield due to the accumulation of inhibiting substances in the digester slurry (e.g., fatty acids). High organic loads lead to higher biogas production and higher instability due to changes in

a composition and an accumulation of VFA. The change of VFA from low to high molecular weight eventually promotes methane inhibition. The accumulation of VFA interferes with the balance of the microorganisms involved in the decomposition organic materials and methane production. The high concentration of VFA decreases pH, resulting in the inhibition of the methanogens, and the subsequent reduction or stop of methane production and a subsequent further accumulation of VFA. The feeding rate of the system must reduce under such circumstances. A low organic load prevents overloading and process failure. However, it also results in low biogas output, resulting in an uneconomical operating point of the digester. Therefore, it is vital to determine a proper OLR to maximize biogas production for each AD system (Sarker et al. 2019). An adequate OLR of a system directly depends on the digester design, substrate concentration, and retention time (Rodriguez 2011). OLR can be calculated in Equation 4 and expressed in kg COD per cubic meter of the reactor for wastewater and kg VS per cubic meter for high solid substrates (Monnet 2003).

$$OLR = COD/HRT \text{ or } VS/HRT \quad (4)$$

4.4 Type of co-digesters

Co-digestion is carried out in a wet single-step process. The selected digester type typically depends on the characteristics of the major feedstock used, mainly TS, digestibility, BMP, and C:N ratio. The proper selection of co-digestion for the available feedstock can enhance biogas yield per m³ of the reactor, with consequent financial benefits for the plant operator. Rabii et al. (2019) reported the suitable type of anaerobic co-digestion systems with different multi-feedstocks to increase the yield of biogas and biomethane. Sarker et al. (2019) summarized the biogas production rate or biogas yield using different reactor configurations concerning operation parameters such as reactor size, type of feedstocks, reactor temperature, pH, OLR, and HRT. Five types of co-digestions, which are Continuously Stirred Tank Reactors (CSTR), Up-flow Anaerobic Sludge Blanket (UASB) reactors, Up-flow Anaerobic Filter (UAF) digesters, Anaerobic Baffled reactor (ABR), and anaerobic lagoon, are described. Wet systems are advantageous when the substrate can directly apply to the fields without separating the solid fraction. For example, feedstocks with high TS concentrations and slurry are mainly treated in CSTRs, while soluble organic wastes are digested in UAF and UASB reactors (Langeveld and Peterson 2018). Table 8 gives the comparison of the anaerobic

process of wastewater with different co-digesters (Woodard 2006).

Table 8 Comparison of anaerobic processes for wastewater treatment (Deublein and Steinhauser 2010).

Reactors	Advantages	Disadvantages	$Kg_{COD}/m^3.day$
CSTR	. Intensive contact between bacteria and substrate . Good decomposition of the suspended material. . Biomass does not need sediment well		1 – 5 $kg_{VS}/m^3.day$
UASB	. Low residence times of 48 h. . No plugging, Natural mixing, and good sedimentation of the sludge.	. High amount of washout of active biomass, depending on the reactor design; recirculation necessary, depending on the substrate; Problems when no granules appear; Sensitive with high concentrations of insoluble organic material	
UAF	. Robust process . No negative effect of irregularities . Good retainment of the microorganisms . Low cost, no agitator required . Plug flow	. Precipitation of inorganics . Filter plugging possible . Short circuit stream possible . High-pressure drop . High demand on construction . Low-stress load of the sludge	10 – 20

		. Not suitable for high sludge concentrations	
ABR	. Long contact time . Advantageous when plug flow supports the anaerobic decomposition	. Low volume load . Not much experience available	
Anaerobic lagoon	. Decomposition of suspended solids over long periods . Possible to work as buffers cheap and straightforward process	. Requires big area required for at least 7 – 30 days residence time . Potential heat loss . Requires periodic sludge removal	<0.5

4.4.1 Continuous stirred tank reactor

Continuous stirred tank reactor (CSTR), known as back mixed reactor or mixed flow reactor, is a continuous wet process that facilitates rapid dilution of reagents through mixing. The mixing system is a crucial design element of this process, and the mixing technology used in this reactor guarantees high efficiency of VSS digestion compared with other methods, but the investment cost of this system is usually higher than the others. At present, 90% of reactors for digestion of high-solid substrates, sludges, and slurries are vertically mounted CSTR-type digesters operating at mesophilic temperatures. This type of reactor suits many of the currently available digestion of a wide variety of substrates from agricultural waste to industrial waste or energy crops with total solid content between 2 and 12% TS. TS values exceeding 15 % can lead to stirring problems in conventional CSTR.

CSTR designs always result in a proportion of bypass, and where this is undesirable. For example, in energy crop digestion, having primary and secondary digesters in series has been shown to maximize specific methane yield (Banks and Ven 2013). The reactor typically has a cylindrical shape with a mixing system, and it can be operated at different temperatures and OLRs around 2–5 kg VS/m³/day. Liquid digestate can be recycled from the second vessel to the first step. This recycling is a valuable tool in the system as it allows for dilution of feedstock and balances the system (Murphy and Thamsiroj 2013).

4.4.2 Up-flow Anaerobic Sludge Blanket

Up-flow Anaerobic Sludge Blanket (UASB) is one of the reactor types where the process is a combination of physical and biological methods. The main feature of the physical process is the separation of solids and gases from the liquid, and that of the biological process is the degradation of decomposable organic matter under anaerobic conditions (Bal and Dhagat 2001). UASB reactors are widely used for the anaerobic treatment of wastewater (Bodkhe 2009). This reactor utilizes methanogenic bacteria or anaerobic microorganisms which form granules as a medium to decompose organic matter into methane and carbon dioxide. The feedstocks flow upwards through the granular sludge blanket in this reactor and kept in suspension in the tank. The combined action of the upward flow of the substrate and the gravity suspends the substrate in the sludge blanket of the reactor. The blanket begins to reach maturity at around three months (Nugroho and Santoso 2019). This reactor is used for domestic and industrial wastewater digestion with low total suspended solid (TSS) because it allows the retention of the anaerobic biomass. UASB reactor belongs to high-rate systems, able to perform anaerobic reactions at reduced HRT (Mainardis et al. 2020). The HRT of 1 day was sufficient to remove more significant than 70% of COD which corresponds to 89% methane concentration for cattle, slaughterhouse, and wastewater (Musa et al. 2018). However, the overcapacity of biomass inside the reactor or the operation during the start-up of granular reactors can reduce the process performance. The flow rate affects biomass content, and a suitable flow rate is vital for the UASB reactor.

4.4.3 Up-flow anaerobic filter

In up-flow anaerobic filter (UFA) reactors, a microbial film (biofilm) grows on an inert support. The biofilm is retained within the reactor on media made from ceramics, glass, engineered plastics, or wood. The filter material typically occupies 60%–70% of the reactor volume. When the water flows through the fixed bed, organic pollution is destroyed by the bacteria that grow inside this fixed bed (Moran 2018). UAF is simple and robust, but care should be taken to maintain the biofilm in optimal condition. The bioreactor operates in both down-flow and up-flow modes. Down-flow is less common but better suited to effluent containing high suspended solid levels. Up-flow mode is used for preventing clogging, channeling, and biomass washout. Thanks to its high separation capacity and good performance in terms of achievable TSS, these reactors are particularly efficient for treating high pollutant content wastewaters such as antibiotic fermentation wastes, yeast production wastewater, brewery, and winery

wastewater, pharmaceutical waste, chemical processing waste, domestic effluent, landfill leachate, and food canning and soft drinks waste (Stanbury et al. 2017). These reactors require a smaller area than CSTRs or lagoons because of their low HRT.

4.4.4 Anaerobic Baffled digesters

Anaerobic Baffled Reactor (ABR) is simple technology with low investment costs. It is typically constructed concrete tanks without mixing systems and possibly internal baffles to differentiate the hydrolysis phase. ABR initially receives the organic fraction of municipal solid waste (OFMSW), liquid effluent from farm or wastewater followed by decomposition process of the materials and eventually produces biogas by microorganisms' activities (Malakahmad et al. 2008). In an up-flow mode, it baffles the direct flow of wastewater through a series of sludge blanket reactors after being transported to the compartment's bottom. The sludge in the reactor rises and falls with gas production and flows through the reactors slowly (Ahmed 2019). ABR does not require the sludge to granulate to perform effectively, although granulation does occur over time (Skiadas et al. 2000). The reactor design has several advantages over well-established systems such as the UASB and UFA, including their simple design, high void volume, reduced clogging, reduced sludge bed expansion, low capital, and low operating cost (Dahlan et al. 2020). Therefore, they give better resilience to hydraulic and organic shock loadings, longer solid retention times, lower sludge yield, and the ability to separate between the various phases of anaerobic catabolism partially. The latter causes a shift in bacterial populations, allowing increased protection against toxic materials and higher resistance to changes in environmental parameters such as pH and temperature. The physical structure of ABR enables important modifications to be made such as the implementing of an aerobic polishing stage, resulting in a reactor that can treat difficult wastewaters which currently require several units, ultimately significantly reducing capital costs (Ahmed 2019).

The process is very stable under shock loads due to its compartmentalized structure; therefore, it is more tolerant to non-settling particles than the UASB while providing long solid retention times. Various modifications have been made to the ABR to improve performance. A modified design of ABR using different combinations of feedstocks can achieve high biogas production and methane generation in the shortest time. Malakahmad et al. (2008) found that the combination of 75% of kitchen waste and 25% of activated sewage sludge produced biogas with a methane content of 74%.

Moreover, the addition of polymer amended reactor shows higher methane yield

compared to the control reactor. Polymer additive could enhance granule formation in the ABR, which promotes phase separation, thus results in a high degree of biomass retention and low solids washout from the ABR. The granulation allows high biomass concentrations in continuous reactors to internal physicochemical gradients within the aggregates and heterogeneous structured populations of syntrophic micro-organisms (Uyanik et al. 2002).

4.5 Anaerobic lagoon

Anaerobic lagoons are used to treat animal wastes or industrial wastes and subjected to high organic loading that anaerobic conditions prevail throughout the entire volume. The biological treatment processes that take place are the same as those that take place in anaerobic digesters. However, it holds longer times for the degradation of compounds that have relatively slow reaction rates. There is no mixing, no heating, and no attempt to control or manage the size or location of the “clumps” of biological solids that develop (Woodard 2006). There are two types of anaerobic lagoons which are simple covered lagoon and improved lagoon.

4.5.1 Simple covered lagoon

Typically, covered lagoons use effluent from 0.5 to 2% solids (Abbasi et al. 2012). OLR and retention time are related to the temperature of the lagoons. For instance, OLR is higher for preheated feedstocks before adding them into lagoons. The OLR loading rates reported for anaerobic lagoons have varied from 0.05 kg/m³ to 2.5 kg/m³ with various digestion temperatures from 10 °C to 40 °C. The HRT is changed from 4 to 250 days, typically 30 to 50 days, and is longer in colder climates. Minimum HRT is 30 days for a simple covered lagoon in Cambodia. The chosen design loading rate depends on the stressed treatment objectives, such as maximizing pollutant reduction, reducing odors, or minimizing sludge production. The minimum treatment volume is based on volatile solids content. Volatile acid concentration is an indicator of process performance because the acids convert to methane at the same rate as formed if an equilibrium is maintained. The lagoon system works well with low volatile acid concentrations (less than 500 mg/L). Inhibition occurs at volatile acid concentrations excess of 2,000 mg/L. The pH value above 8 favors more ammonia emissions, while below pH 6 favor more hydrogen sulfide and carbon dioxide emissions. All the parameters for obtaining the optimum and extreme operating ranges for methane formation from these digesters are listed in Table 9 (Bowman and Dahab 2002).

Table 9 Ideal operating ranges for methane fermentation (Bowman and Dahab 2002).

Parameter	Optimum	Extreme
Temperature (°C)	30 – 35	25 – 40
pH	6.6 – 7.6	6.2 – 8.0
Alkalinity (mg/L)	2,000 – 3,000	1,000 – 5,000
Volatile acids (mg/L)	50 – 500	2,000

4.5.2 Improved covered lagoon

The improved lagoon functions are similar to UASB, in which the wastewater is inserted, distributed over the bottom but lower investment cost (Mainardis et al. 2020). The improved lagoon controls the physical, chemical, and biological environments to achieve high degradation efficiency, high biogas production, and process stability (Schmidt et al. 2019).

4.5.3 Design and construction cost of the covered lagoon

The covered lagoon's design is simple compared to other digester models, consisting of one or more lined, in-ground lagoons with flexible gas covers to collect rising biogas and a pond to store the digested waste (Figure 6). Raw wastewater or other effluents enter near the pond's bottom and mix with the active microbial mass in the lagoon. Covered lagoons are rarely heated or insulated. A typical anaerobic lagoon is a relatively deep earthen basin with an inlet, an outlet, and a low surface-to-volume ratio, permitting settlable solids' sedimentation to digest the retained sludge.

This system allows anaerobically reduce some of the soluble organic substrates. If the basin is not excavated from the soil of very low permeability, it must be lined to protect the groundwater below. The lagoon should be lined with an impermeable material such as plastic, rubber, clay, or cement. Covers are most often manufactured from HDPE and must be strong to resist rain or storm on the lagoon surface and freeboard. Lagoons vary in depth from 2.5 to 9 m and build as deep as the local geography allows to minimize the surface area and reduce odor emissions. Depth approaching 6 m is recommended to reduce the surface area and to conserve heat in the lagoon. The lagoon should be designed to avoid short-circuiting feedstock and incorporate a minimum freeboard of 0.9 m (Bowman and Dahab 2002).

The direct cost of constructing an anaerobic lagoon is the cost of the land, the excavation of the lagoon, and the cover. Costs for forming the embankment,

compacting, lining, service road, fencing, and materials like clay, concrete, piping, and pumps must also be considered.

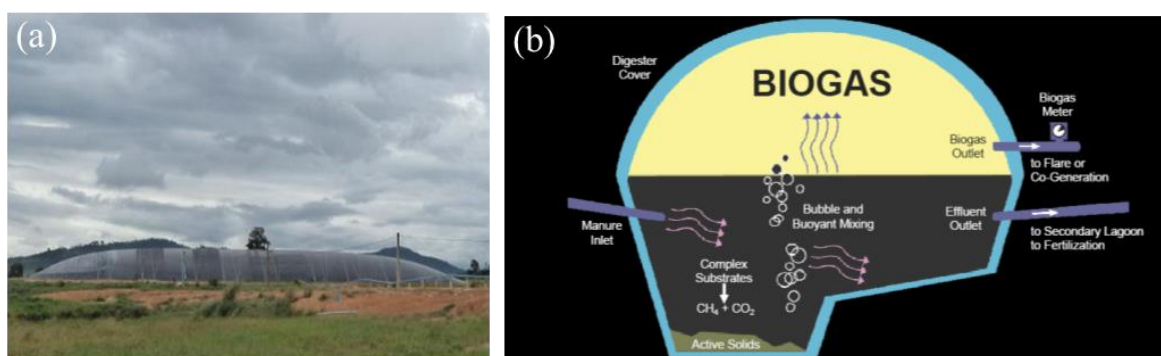


Figure 6 (a) Anaerobic covered lagoon technology and (b) biogas production process.

4.5.4 Operation and maintenance

The operation and maintenance requirements of a lagoon are minimal. A daily grab sample of influent and effluent should be taken and analyzed to ensure proper operation. All the parameters should be in the operating ranges for methane formation, as indicated in Table 9. A rate outside of these extreme ranges will decrease the rate of methane formation. Aside from sampling, analysis, and general upkeep, the system is virtually maintenance-free. Solids accumulate in the lagoon bottom and require removal on an infrequent basis (5 – 10 years), depending on the inert material in the influent and the temperature. Sludge depth should be monitored annually (Bowman and Dahab 2002).

4.5.5 Advantages and disadvantages of anaerobic lagoons

The advantages of lagoon systems include designing a large volume system at a relatively low investment cost. Low construction and operating costs make anaerobic lagoons financially attractive alternatives to other treatment systems, although sludge must occasionally be removed. This system is particularly interested in low TS/energy content substrates like industrial wastewaters, municipal wastewater, or liquid manure

(Talia 2018). It is the cheapest solution for anaerobic digestion process application and is easy to operate. Covered lagoons are a good way to recover methane gas and control ammonia and other odorous gases. In some cases, the layer of solids that forms on the lagoon's surface due to floating greases, oils, and the products of microbial metabolism (the scum layer) has successfully prevented intolerable odor problems.

However, there are disadvantages like the high tendency to form sedimented layers at the bottom of the system. It might necessitate opening and emptying the system imposing high maintenance costs. Other disadvantages include huge area necessary, low efficiency due to non-controlled temperature of digestion, possible technical problems due to high volume of gas storage, leakage, etc. Anaerobic lagoon technology has been shown to emit pollutant substances (through gas emissions and lagoon overflow pathways) that can cause adverse environmental and health effects. Moreover, anaerobic lagoons do not apply to many situations because of extensive land requirements, poor process control, sensitivity to environmental conditions, and objectionable odors. The anaerobic process may require long retention times, and anaerobic bacteria are ineffective below 15 °C, which reduces the rate of methane production. The low temperature has a negative impact on degradation efficiency, biogas production, and process stability (Schmidt et al. 2019). Therefore, anaerobic lagoons are not efficient biogas producers in cold climates.

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CHAPTER 5 BIOGAS PRODUCTION AND UTILIZATION

The main components of biogas production, biogas pre-treatment, and biogas upgrading are discussed. Biogas utilization for the production of electricity, heat, and fuel is highlighted. Biogas flares are used for safety and environmental reasons, and some critical parameters for flare design and its operation and maintenance will be discussed.

5.1 Biogas properties

The energy content of biogas from AD is chemically bounded in methane. The composition and properties of biogas vary to some degree depending on feedstock types, biogas technology, digestion systems, temperature, retention time, etc. (Seadi et al. 2008). Biogas mainly consists of combustible CH_4 and non-combustible CO_2 , H_2O , and traces of NH_3 , H_2S , and other trace gases. The CH_4 content makes it suitable for various energy uses. Table 6 in Chapter 3 shows potential methane yields for different feedstocks, and its yield from other feedstocks can be found in a previous study (Seadi et al. 2008). Some impurities such as H_2S and NH_3 need to be reduced to allowable levels. Typical H_2S levels allowed for combustion engines or generators and natural gas upgrading are < 200 ppm and <10 ppm, respectively. Unfortunately, H_2S content in biogas is usually at concentrations between 10 – 10,000 ppm depending on the feedstocks (Allegue and Hinge 2014). For instance, H_2S content from organic waste varies from 10 to 2,000 ppm, whereas its value is relatively low for biogas from sewage sources (Rasi et al. 2007). In Cambodia, biogas production from piggery farms contains H_2S around 2,000 – 3,000 ppm (Lyhour, 2020). This H_2S is harmful to humans and the environment and corrodes equipment such as biogas storage tanks and containers, pipelines, compressors, engines, etc. H_2S can be oxidized to sulfur dioxide (SO_2) combustion. SO_2 in high concentrations affects breathing and may aggravate existing respiratory and cardiovascular diseases. SO_2 is also a primary contributor to sulfuric acid (H_2SO_4), which is high toxicity at low concentrations and leads to corrosion in appliances.

Furthermore, a high concentration of H_2S in biogas is undesirable because releasing this gas during biogas collection may lead to pulmonary edema for humans. It has been stated that the concentration of H_2S between 500 – 1,000 ppm possibly

affects with rapid loss of consciousness and death, and its content of more than 1,000 ppm causes instantaneous human death on first breath (Doujaiji and Al-Tawfiq 2010) (Sawalha et al. 2020). Therefore, it is recommended to remove or reduce its content directly in the digester during the AD process or treat the raw biogas before utilization or upgrading. In the digester, H₂S separation can be carried out by adding oxygen in the digester to induce biological desulphurization (microorganisms consuming oxygen) and convert H₂S to elementary sulfur. Other options are also possible to separate H₂S, e.g., by adding iron salts into the substrate. However, the pre-treatment process is the most commonly used method.

5.2 Biogas pre-treatment

Biogas pre-treatment is a process to remove H₂S, NH₃, siloxanes, and other unwanted constituents. The technologies used to remove H₂S can be divided into physical, chemical, and biological methods (Wellinger et al. 2013). The physical-chemical desulphurization method typically involves technologies that employ physical or chemical phenomena in preventing or limiting the formation of H₂S during the anaerobic digestion process (Okoro and Sun 2019). This method typically uses adsorption like activated carbon (Sawalha et al. 2020), iron oxides, zinc oxides (ZnO), absorption/scrubbing, biotechnological (air/oxygen injection into the digester). Additionally, the combination of two or more processes can achieve high efficiency of H₂S removal. The combined physical-chemical and biotechnological by using chemical absorption with iron salts and the microbial regeneration of the solution has been developed and described in the literature (Allegue and Hinge 2014).

5.2.1 Iron oxide pellets

Reaction with iron oxide or ferrous oxide (Fe₂O₃), usually absorbed in pellets or other carrier materials, is a type of chemical treatment method which is low cost and gives high efficiency of H₂S removal. The iron oxide reacts with the H₂S to produce iron sulfide, in which the S element remains on the surface covers the active iron oxide surface. The iron oxide pellets, or wood chips impregnated with iron oxide, known as iron sponge, are the most recognized adsorbent in the industry with potential H₂S reductions > 99.9%. This adsorbent can operate in conjunction with a small airflow into the system and the biogas input to promote continuous regeneration. The H₂S removal rate is up to 2.5 kg/kg Fe₂O₃ for continuously regenerated systems with <1% oxygen input (Axelsson et al. 2012). The proprietary iron oxide-based scrubbing systems can

remove up to 2000 ppm of H_2S at 40 °C, with a biogas flow rate of 1,000 Nm^3/h in a full-scale AD system, resulting in 2 Nm^3 of H_2S removed per hour (2.9 kg $\text{H}_2\text{S}/\text{h}$). The biogas should not be too dry because the reaction needs water. It should avoid condensation because the iron oxide material can stick with water, reducing the reactive surface (Choudhury et al. 2019).

5.2.2 Case study of biogas pre-treatment system in M's pig farm in Cambodia

The electricity generation from biogas at M's pig farm has been up and running in the farm; however, the corrosion from H_2S led to rapid deterioration of the generator engines, increased maintenance costs, and short lifespan of the generators. A biogas pre-treatment system was purchased from CAMDA (China Agricultural Machinery Distribution Association), China, installed in December 2019. It consists of four desulfurized tanks (2×2 parallel tanks connected in series), a blower, a moisture separator, and an electrical panel (Figure 7). First, biogas enters two desulfurized tanks, passes the blower to stabilize the pressure, and maintains a constant biogas flow. Then it passes through the second set of desulphurization tanks and finally via a moisture separator to remove moisture and dust with a cyclone. According to CAMDA's technical standard, its biogas treatment capacity is 250 Nm^3/h with an H_2S content of 2000 ppm. The pressure at the outlet can be set between 4 – 40 kPa. Ferrous oxide pellet adsorbent was used to remove H_2S from raw biogas. Each tank is filled with 600 kg of pellets and changed every 720 working hours. The efficiency of H_2S reduction is up to 97.3% (Table 10).



Figure 7 Biogas pre-treatment unit at M's Pig farm.

Table 10 Biogas quality before and after pre-treatment with ferrous pellets.

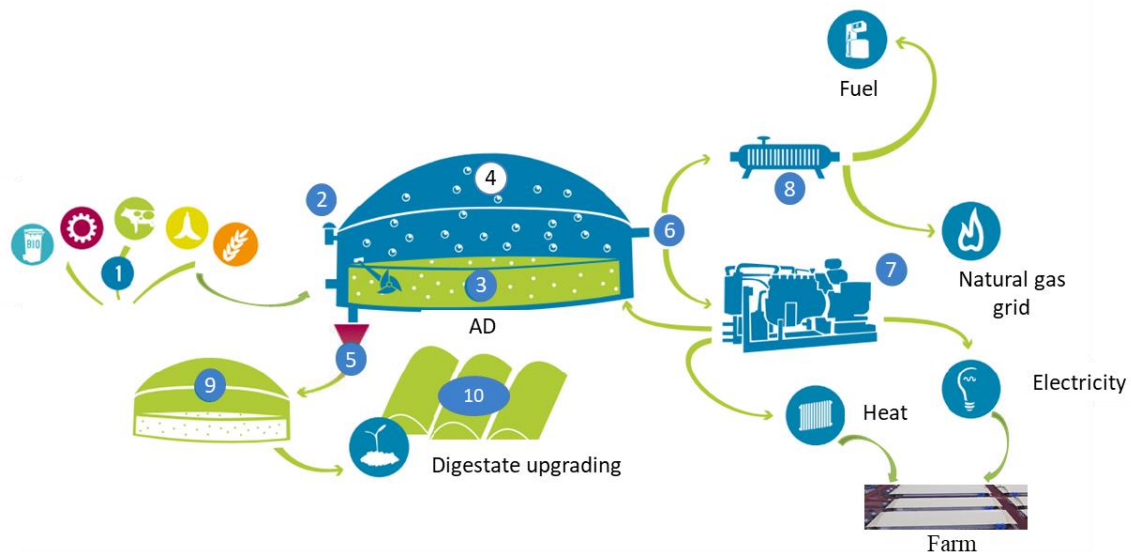
Biogas composition	Before pre-treatment	After pre-treatment
CH ₄ (%)	66	68.1
CO ₂ (%)	28.4	29.1
O ₂ (%)	0.8	0.3
H ₂ S (ppm)	2,266	59
Balance (%)	4.9	2.5

5.3 Biogas Utilization

AD systems produce raw biogas and by-products (liquid digestate). Biogas is a methane-rich gas that can produce energy when combusted. The energy content of the gas is mainly based on its methane content. A certain carbon dioxide and water vapor content are unavoidable, and H₂S content must be minimized. The impurities can affect the equipment for biogas utilization by causing problems such as corrosion and mechanical wear and lead to unwanted emissions when the biogas is combusted. There are different aspects of quality demands for biogas utilization. Biogas, therefore, may need to be cleaned or processed before end-use as combined heat and power (CHP) or biomethane.

For instance, biogas can be converted to electricity using an electrical generator. In contrast, biogas upgrading produces biomethane as fuel for combustion engines or compression natural gas (CNG) in gas cylinders or pipes for household or filling stations (Holm-Nielsen et al. 2009). Figure 8 illustrates the schematic of biogas production and utilization.

Figure 8 Schematic overview on biogas production and use technologies at industrial scale: (1) Different feedstocks, (2) safety equipment, (3) anaerobic digester, (4) gas storage, (5) sanitation, (6) gas cleaning system for desulfurization, (7) combined heat and power unit (CHP), (8) gas treatment system for biogas upgrading (fuel and CNG), (9) Digestate storage, and (10) digestate upgrading (optional).



5.3.1 Electricity production

Biogas can be converted directly into electricity by using gas turbines, fuel cells, or electric generators. Besides using biogas in conventional reciprocating internal combustion engines, it can also be used in gas turbines. The biogas is mixed with air and pressed into a combustion chamber at high pressure in a gas turbine. The air-biogas mixture is burned, causing a temperature increase, and the hot gases are released through a turbine connected to the electricity generator. However, this technique typically has a capacity to energy below 200 kW, and the cost of micro-turbine is relatively high.

Another option for converting biogas to electricity is using fuel cells. Fuel cells are electrochemical devices converting chemical energy directly into electrical energy. The fuel cell structure consists of a porous anode and cathode and an electrolyte layer in contact between them. When biogas is fed to continue to the anode, and oxygen is fed to the cathode, an electrochemical reaction occurs at the electrodes, producing an electric current. The conversion efficiency depends on the selection of electrolyte membrane (Seadi et al. 2008). However, the fuel cell process is expensive and requires very clean gas. On the contrary, converting biogas to electric power by a generator set is more practical since the raw biogas does not need to be just as clean. It is important to note that selecting generator capacity for a biogas plant can give high electricity conversion efficiency and minimize the equipment and operation cost. Generator efficiency is a function of scale and loading rate.

A case study of electric production at M's Pig farm: Four simple covered lagoon (76,000 m³), located at Keo Pos, Steung Hav, Preah Sihanouk, with a total pig of 41,100 heads indicated that the biogas production is 4,860 Nm³/d, and it requires two generators with each sized 800 kVA to generate the electricity. Due to the conversion loss, 1 m³ biogas can convert to approximately 1.7 kWh of energy. The total electricity production covers about 80% of the annual farm electricity demand

5.3.2 Combined heat and Power

The combined heat and power (CHP) generation is a standard utilization of biogas from AD, which is a very efficient method for producing electricity and heat from a renewable energy source. An engine-based CHP power plant can efficiently up to 90%, producing up to 35% electricity and 65% heat. In this case, the Gas-Otto engine is a part of electricity generators specifically used for biogas (minimum 45% CH₄) operating with air surplus to minimize carbon mono oxide (CO) emission. It leads to lower gas consumption and reduced motor performance using an exhaust turbocharger (Seadi et al. 2008). The produced electricity from biogas as energy for electrical equipment in the farm or industry, and the excess electricity can sell to the grid.

5.3.3 Heat Utilization

Besides the CHP process, heat can be produced by burning biogas in boilers either on-site or transported by pipeline to the end-users. Biogas does not need any upgrading, and the contamination level does not restrict the gas utilization as much as in other applications. Biogas generally does need particulate removal, compression, cooling, and drying. However, many biogas plants have been established exclusively for electricity production, without consideration for using the produced heat. An important issue for the energy and economic efficiency of a biogas plant is utilizing the produced heat. Therefore, newly established biogas plants should include heat utilization in the overall plant design (Seadi et al. 2008). Usually, a part of the heat is used to heat the digesters (process heating). The rest can be used for external needs such as industrial processes and agricultural activities (drying crops). Heat is also used in power heat cooling coupling by converting input energy into cooling through absorption.

A case study on biogas heat utilization in Cambodia: A local heat demand in Cambodia is given at facilities for food processing and industrial companies. Coal is used in boilers for producing steam or hot water. The retail coal price in Cambodia is about 0.37 US\$/kg, which is equal to a price of 0.046 US\$/kWh. Heat supply from

biogas plants with a capacity of 100 Nm³/h and 10 Nm³/h cost 0.03 and 0.05 US\$/kWh, respectively. On the other hand, biogas use for heat supply and transport in biogas pipelines (< 5 km by distance) costs 0.047 US\$/kWh (Scholwin and Hofmann 2019). Based on the economic evaluation, heat supply (nearby or transport in biogas pipeline) for industrial purposes from large scale biogas plants can be an alternative utilization pathway.

5.3.4 Biomethane production and CNG

Biogas utilization as a substitute for natural gas has gained importance due to the depletion and low quality of natural gas resources (Ullah Khan et al. 2017). CH₄ can make clean fuel, but CO₂, a non-combustible part of the biogas, leads to a lower calorific value. For example, 55% CH₄ has a calorific value of 19.7 MJ/Nm³, while pure CH₄ has 35.8 MJ/Nm³ (Abderezzak et al. 2012). Therefore, biogas cleaning and upgrading are necessary to increase the gas's calorific value and reduce the contamination of technically or environmentally hazardous components. Some impurities, e.g., H₂S, are harmful to the upgrading process and must be removed (Wellinger et al. 2013). Impurities are removed in the upgrading step to obtain the composition requirements, as stated in Table 11, but depending on which upgrading technology is used. The equipment for biogas upgrading to natural gas quality needs additional investment. Biogas upgrading technologies such as pressure swing adsorption (PSA), high pressure water scrubbing (HPWS), organic physical scrubbing (OPS), chemical scrubbing process (CSP), membrane separation, and cryogenic separation have been used. The selection of an efficient method for upgrading biogas is critical to be of equal quality as natural gas and to minimize the production cost and GHG emissions. Ullah Khan et al. (2017) studied different technologies of biomethane production and their advantages and disadvantages in terms of the technical features of upgrading technologies, various specific requirements for biogas utilization, and the appropriate investment and operating and maintenance costs. In general, membrane separation technology has better performance in terms of economic and environmental aspects in comparison to traditional separation processes. The future membrane material development could bring down biomethane production costs.

On the other hand, the capital and operating costs of biogas upgrading technologies largely depend on the selected process, quality of raw biogas, desired product quality, and more importantly, the capacity of the plant, e.g., the bigger the capacity, the higher the specific investment cost (Bauer et al. 2013). Biomethane

production has developed mainly in countries with a strong economy in general and with high goals regarding greening the economy and cases where a specific biogas capacity (mostly above 500 m³/h biogas) can be realized at a production site (Backman and Rogulska 2016).

Biomethane can be compressed to form CNG (Compressed natural gas) and used as fuel to power motor vehicles. The costs mainly depend on the volume rate, in which 500 Nm³/h is considered the lowest economic scale. A recent study by FvB (2018) showed that CNG from biomethane is unsuitable for Cambodia due to biogas capacity and lack of filling stations. Moreover, LPG price is lower than CNG from biogas upgrading, e.g., LPG price is 0.58 US/kg (equaling to 0.045 US/kWh), whereas CNG is 0.053 US/kWh and 0.089 US/kWh for 100 Nm³/h and 10 Nm³/h of biogas production.

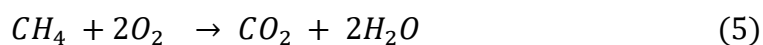
Table 11 The compositions of biogas versus biomethane.

Biogas composition	Biogas	Biomethane
CH ₄ (%)	50 – 70	> 97
CO ₂ (%)	30 – 45	< 3
H ₂ S (ppm)	< 6,000	< 5

5.4 Flaring

Biogas flares are used to safely burn biogas surplus to the demand of the biogas utilization system or where biogas consumption is interrupted. They may also provide the only means of safely disposing of biogas produced by anaerobic bioprocesses where the economics of energy recovery have proved unfeasible (Caine 2000; Seadi et al. 2008). There is a risk for fire or explosion when methane concentration is in the range of 5 – 15% in the air. Flaring of biogas is the oxidation of methane in an open flame, resulting in the emission of carbon dioxide rather than methane, which has a global warming potential of more than 25 times CO₂. Complete combustion of one mole of methane requires two moles of oxygen (Equation 5). However, in the air, 5.8 volume of air containing 21% v/v to complete combustion of 1 volume of biogas containing 60% v/v methane. In theory, providing excess air (10 V_{air} to 1 V_{CH₄}) achieves the combustion and cools the flame. The design of biogas flare is based on the biogas

composition (air requirement of the flame) and flow rate (to calculate the height of flare and velocity and residence time of the biogas in the flame) (Nikiema et al. 2007).



The enclosed flare system is equipped with air dampers to control combustion temperature (Figure 9). It is more likely used than an open flare system because it can prevent quenching, resulting in uniform burning and low emission. Therefore, this system can meet the performance and emission standards and be further engineered to meet specific sites (Caine 2000).



Figure 9 An enclosed flare from CAMDA.

5.4.1 Operation, caution, inspection, and maintenance

A flare inspection test is needed before operation. After installing flare and control equipment, the gas supply pipe network must check for correct installation using the leak detection method and gas pipe network inspection standard (Seadi et al. 2008). For safety reasons and minimization of thermal and noise emissions from flaring,

installing a flare tower should be installed at a safety distance of at least 20 meters. The flare, including the heated kinetic energy equipment, should be installed in ventilated and away from flammable and explosive objects. The methane content of biogas should be regularly tested. The equipment cannot be turned on when methane content is less than 35%.

The electric valve of the flare (flow control valve) is a key component for supplying and cutting off the gas. Therefore, the electric valve should regularly be inspected and maintenance no longer than three months. Leakage of the electric valve can cause accidents, and its damage or blockage results in fuel not being supplied to the burner.

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CHAPTER 6 UTILIZATION OF DIGESTATE

Digestate properties (the nutrient quantity) and quality of digestate and quality management will be discussed in this chapter. Also, digestate upgrading and advantages of this technology are reviewed. The standardization of digestate is given, and the utilization of digestate as organic fertilizer in Cambodia is highlighted.

6.1 Digestate properties

Digestate, a by-product of AD, consists of a solid and a liquid fraction and can be used as fertilizer on the fields to improve plant nutrients utilization, reduce mineral fertilizer consumption, and reduce water pollution. Recycling digestate to land is the best practicable environmental option in most circumstances, completing natural nutrient cycles. Digestate is a valuable source of significant plant nutrients. The nutrients such as N, P (refer to P_2O_5), K (refer to K_2O), S (refer to SO_3), and other elements present in the biogas feedstock will remain in the process and be available in the digestate. These nutrients are essential for plant growth and sustainable crop production (Chambers and Taylor 2013). The nutrients compositions of digestate remain the same as feedstocks, but they have better-fertilizing quality because the organic molecules are digested, and part of the nutrients are mineralized.

6.2 Digestate quality and management

The amount of nutrients in the digestate is much dependent on feedstocks, and therefore the quality of fertilizer differs. High-quality digestate fits for use as fertilizer is defined by essential features such as declared content of nutrients, pH, dry matter and organic dry matter content, homogeneity, purity (free of inorganic impurities such as plastic, stones, glass, etc.), sanitized and safe for living organisms and the environment with respect to its content of biological (pathogenic) material and of chemical pollutants (organic and inorganic) (Seadi et al. 2012). The digestate can be recycled as excellent fertilizer but is limited by insufficient confidence in its quality, impacting food safety, health, and the environment. Inappropriate handling, storage, and application of digestate as fertilizer can cause ammonia emissions, nitrate leaching, and overloading of phosphorus. Periodical sampling and analyzing the nutrients content must be done before integrating on the field to ensure that the standardization of digestate can be met. Therefore, the application of digestate as fertilizer must be made on the basis of digestate quality control and management (Holm-Nielsen et al. 2009).

The quality management of digestate guarantees that digestate is safe for use and contributes to the perception of digestate as a safe and healthy product. The ultimate aim is to enhance digestate utilization as fertilizer and provide incentives for further developing biogas technologies, which are environmentally sound and veterinary safe treatment options for animal manures and suitable organic wastes (Seadi et al. 2012). Quality requirements necessarily imply adopting a unified approach and a system of quality parameters to measure and guarantee quality. Digestate quality management is implemented through various means: standards of digestate quality, digestate certification systems, nutrient regulations, and legislative frameworks, and most important, through ongoing quality control practices along the whole digestate production cycle. The production and recycling of digestate as fertilizer requires quality management and quality control throughout the entire closed process of AD, from the output of the AD feedstocks until the final utilization of digestate as fertilizer (Figure 10).

The increasingly strict environmental legislation introduced in most countries aims to address pollution of all kinds and losses of biodiversity and minimize any current and future hazards for living organisms. Legal frameworks and quality standards for digestate used as fertilizer provide confidence in digestate quality and safety and contribute to a sound and stable market for digestate. Such regulations, introduced by an increasing number of countries, include standards of digestate quality, digestate certification schemes, guidelines for recommended practices for digestate utilization, and positive lists of materials suitable for use as AD feedstock. The rigorous selection and strict quality control of the materials used as feedstock for AD is the first and most crucial step of digestate quality management, ensuring maximum ecological and economic benefits from digestate as a fertilizer (Mucha et al. 2019). The unsuitable waste categories containing heavy metals, persistent organic compounds, pathogen contamination, and other potential hazards cannot degrade during the digestion process. It is needed to remove those unwanted compounds (AD feedstocks treatment) and treat the digestate (Holm-Nielsen et al. 2009). The main aspects of quality management of AD residues (digestates) such as chemical, biological and physical impurities are listed in the literature (Seadi et al. 2012).

Good practice in digestate quality management improves overall confidence in

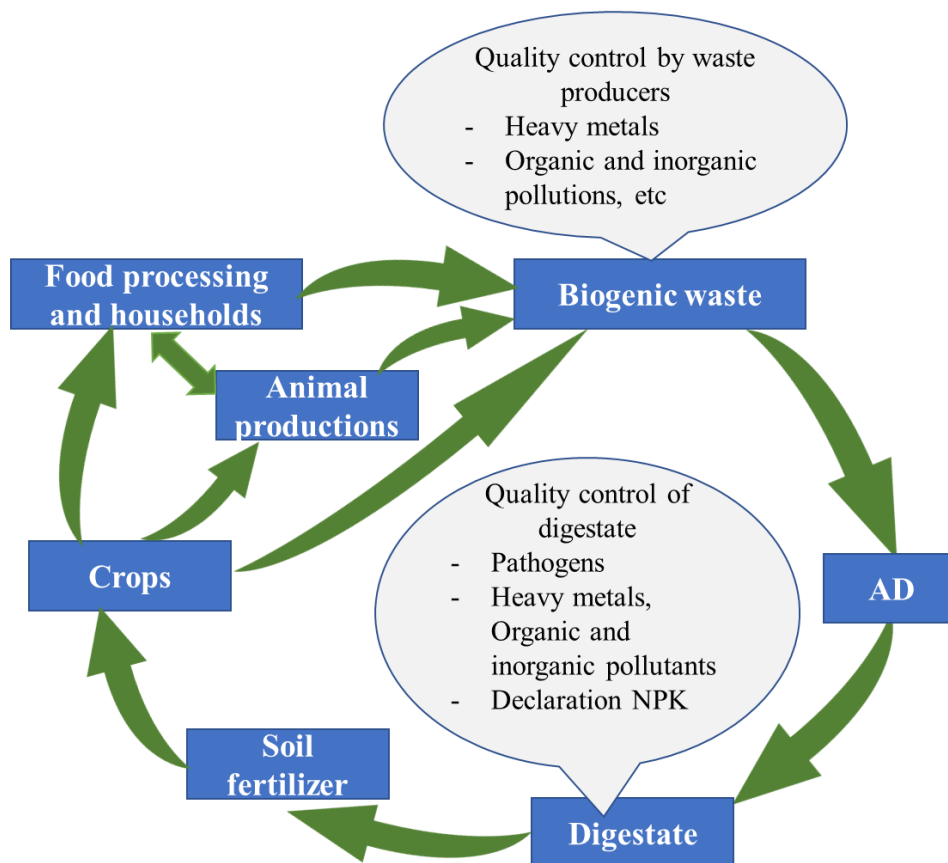


Figure 10 Schematic representation of the closed cycle of anaerobic digestion of biogenic waste, AD, and quality management of digestate.

digestate and veterinary safety, prevents health and environmental hazards, positively affects food safety and better market conditions for high-quality digestate, and creates incentives for AD development. The displacement of mineral fertilizers by organic fertilizer lowers the negative impact on the environment (breaking the chain of pathogen transmission). It increases the recycling of organic matter, nutrients, and conservation of natural resources. In addition, it offers cost savings to farmers by reducing purchases of mineral fertilizer but gives higher nutrient efficiency through enhanced use of own resources (Seadi 2001).

6.3 Digestate preserving and characteristic condition

Unlike raw animal manure and other AD feedstock, sanitized digestate poses minimal risk of pathogen transfer through handling and application. It is essential to avoid recontamination from raw manure and slurries, re-growth of bacteria in biowaste

after pasteurization and digestion, and other un-sanitized materials and sources (Bagge et al. 2005). Precautions must be taken at the biogas plant and other digestate storage areas to preserve the high quality of digestate until its final utilization as fertilizer. The proper storage, handling, and application of digestate preserve its value and qualities as fertilizer. It helps prevent losses of ammonia and methane to the atmosphere, nutrient leakage, runoff, and emissions of unpleasant odors. Digestate can be stored at the biogas plant, or even better, at a convenient location close to the fields where it will be applied as fertilizer. Independent of site, digestate stores are usually above-ground storage tanks. Lagoons and storage bags can also be used. In all cases, it is imperative to cover the storage facilities as this prevents nutrient losses and pollution through ammonia emissions and from residual methane production and digestate dilution by rainwater (Mucha et al. 2019).

Before digestate is used as a fertilizer, its composition should be analyzed and declared according to best farming practices. It also applies to digestate produced and used on a single farm. Declaration of macro-and micro-nutrients and dry matter content is part of the quality assurance schemes for digestate in many countries (Seadi et al. 2012). Usually, large-scale biogas plants install a small laboratory on-site for measuring the dry matter content, the dry organic matter, and the pH of samples from all loads of digestate. Accredited laboratories can analyze more complex nutrient content. Specific protocols should stipulate the frequency and the procedure for sampling and analysis to avoid uncertainty.

Digestate can be used as fertilizer without further treatment after its removal from the digester and after the necessary cooling. When used as fertilizer, digestate is transported away from the biogas plant, through pipelines or with special vacuum tankers, and temporarily stored in storage tanks placed, e.g., out in the fields, where the digestate is applied. The total capacity of these facilities must be enough to keep the production of digestate for several months. In many European countries, agricultural legislation requires six to nine months storage capacity for animal manure, slurry, and digestate to ensure their optimal and efficient utilization as fertilizer (Seadi et al. 2008).

6.4 Digestate treatment and upgrading

The carbon content in the digestate is significantly reduced during AD since the organic matter is transformed into CH_4 and CO_2 . A part of organically bound nitrogen is mineralized, and ammonia in the digestate is higher than other organic fertilizers.

Storage can cause a decrease in the total solids, chemical oxygen demand, and alkalinity of the digestate (Laureni et al. 2013). An excess of nutrients present in the digestate can cause environmental problems. As digestate usually has low dry matter content, its storage, transport, and application are expensive. It makes digestate processing and volume reduction an attractive option. Thus, the digestate needs to be processed to manage its volume (Möller and Müller 2012).

Digestate processing can involve many different treatments and technologies depending on local needs, for instance, enhancing the quality and marketability of the digestate, producing standardized fertilizers, or removing nutrients and organic matter from the effluent (Figure 11). Treatment technologies include physical (e.g., solid-liquid separation), chemical (e.g., flocculation, precipitation), and biological (e.g., composting) approaches. Digestate processing can be partial or complete by separating the digestate into solid fibers, fertilizer concentrates, and pure water (Seadi et al. 2012). The first step of each digestate treatment procedure is the physical solid-liquid separation. This partial processing uses relatively simple and cheap technologies, e.g., screw-press separators or decanter centrifuges, to obtain high DM (20–25%) solid manure and low DM (5–7%) liquid manure. The composition of separated solid digestates dramatically varies, as stated in a previous study (Möller and Müller 2012). Decanter centrifuges separate most phosphorus in the digestate into the fiber fraction (Seadi et al. 2008). The Phosphorus separation improves the management of macronutrients because it enables the separate application of phosphorus and nitrogen. Removal of particulate nitrogen can be performed by solid-liquid separation, while ammonia removal can be achieved through chemical/physical and biological processes (Mucha et al. 2019).

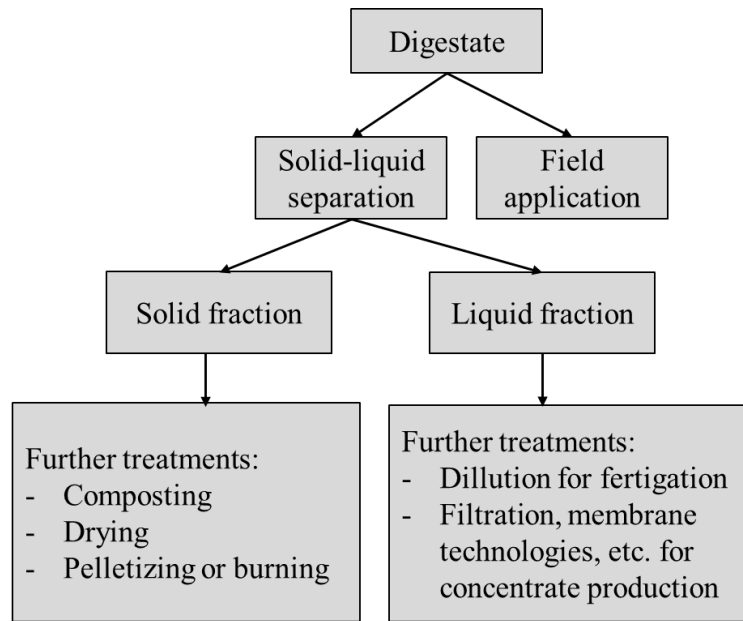


Figure 11 Digestate processing, treatment, and applications (Möller and Müller 2012).

The solid fraction can be applied directly as fertilizer in agriculture or dried for intermediate storage for enhanced transportability. The solid fraction can also sell as a phosphorus-rich fertilizer without any further treatment. The liquid fraction, containing the main part of N and K, can be applied as liquid fertilizer. Additional treatments, such as drying solid digestate or water removal from liquid manure by membrane technologies to produce concentrates, are not widespread (Möller and Müller 2012).

6.5 Standardization and regulation of digestate

The use of digestate in agriculture as fertilizer or the land application as a soil conditioner has important advantages, such as reducing dependence on chemical fertilizers and peat and closing the cycle of nutrients. Good management in the end destination of digestate will reduce the climate change impact of the waste. However, some health and environmental concerns over the amount and composition of digestate to the selected end destination have been identified (Theng et al. 2014). The use of quality standards for organic materials in agricultural land must follow the regulation to prevent any potential negative effects on soil, vegetation, and animal and human health. Although the strategic framework and the policy on biodigester development in Cambodia have been set to promote and support waste to energy through digester

technology, yet the standardization (quality and utilization) and regulation system on by-products (digestates) from biodigester remain unclear. In addition, lacking the equipment required to conduct chemical testing to ensure the rigorous quality control of fertilizers is another factor that affects fertilizer management and usage. The limited inspection and certification capacity of the Department of Agricultural Legislation (DAL) and MAFF inspectors is a problem that needs to be urgently addressed to control the quality of fertilizer and its market. Therefore, digestate management and utilization need to be included in the digester framework and policy.

Lesson learned from Europe: In 2002, the regulation for animal by-products treatment, including the requirements for their safe application to land, was introduced, following the European outbreaks of Bovine Spongiform Encephalopathy (BSE). The Regulation 1774/2002, known as the Animal By-Products (ABP) Regulation and superseded by the current Council Regulation 1069/2009, stipulates the categories of animal by-products and the condition in which these can be used as feedstock for AD (Seadi et al. 2012). When the digestate is used as fertilizer, the regulation of this end destination has three approaches. One describes the requirements for waste to become a product according to a waste law or environmental regulation. Another approach is based on the evaluation of digestate and end destination, taking into account the characteristics of the soil and application rate, among other parameters, according to recognized protocols and standards. Finally, the use in agriculture requires previous registration as a fertilizer according to fertilizer regulation. The animal by-products regulation also applies as a guideline to the digestate production and end destination because these are potential feedstocks and influence digestate composition Mucha et al. (2019).

One of the critical aspects regarding recycling digestate is the load of nutrients on farmland. Nitrate leaching or phosphorus overloading can occur due to inappropriate handling, storage, and application of digestate as fertilizer. In Europe, the Nitrate Directive (91/676/EEC) restricts nitrogen input on farmland to protect the ground and surface water from nitrate pollution and allows a maximum of 170 kg N/ha/year. Nutrient loading on farmland is regulated by national legislation in most European countries (Seadi et al. 2008).

6.6 Utilization of digestate as organic fertilizer

Organic fertilizer is a component of sustainable agriculture apart from soil mineral provision, which contributes to soil quality by improving soil structure, chemistry, and biological level. The utilization of digestate as organic fertilizers can improve soil fertility and produce healthy crops with high yields. It helps to enhance and shape the overall health of agricultural soils (Jaja and Barber 2017). Organic matter from digestates improves soil aeration and water infiltration, and it also enhances both the water and nutrient holding capacity of soils. It also increases water retention by the soil and is essential in maintaining soil tilth. Organic fertilizers are responsible for the formation of soil aggregates which are very necessary for maintaining soil fertility. It is needed for plant growth not only crops grown that year but will continue to influence crops in the succeeding years because decomposition of the organic matter is not completed with one year. The utilization of organic fertilizers provides growth-regulating substances and improves soil's physical, chemical, and microbial properties (Jaja and Barber 2017).

However, the application of organic fertilizer must be based on a proper fertilizer plan to get more benefits in terms of high crop yields, higher cost-effectiveness, and environmental aspects. The fertilizer plan is elaborated for each agricultural field, according to the type of crop, the planned crop yield, the anticipated utilization percentage of nutrients in digestate, the type of soil (texture, structure, quality, pH), the existing reserve of macro and micronutrients in the soil, the pre-crop and the irrigation conditions and the geographic area. Experience from Europe indicates that the most economical and environmentally friendly strategy of applying digestate as fertilizer is by fulfilling the phosphorus requirement of the crops with phosphorus from digestate. Application of digestate to fulfill the phosphorus requirement also implies a partial fulfillment of the nitrogen requirement of the crops. The remaining nitrogen requirement can be completed by applying mineral fertilizer (Seadi et al. 2008). However, the specific content of those organic fertilizers highly depends on the soil nutrient in different locations and countries. Soil nutrients in other areas and nutrients requirements for agriculture in Cambodia are discussed in section 6.7.1.

Besides the requirements of nutrients for specific soil and crop types, for optimum utilization of digestate as organic fertilizers, good agriculture practice guidelines are required. Storage capacity for digestate should be a minimum of 6

months, and application techniques minimize N loss. For example, optimum weather conditions for applications of digestate are rainy, high humidity, and no wind. Application as top fertilizer on crops in rich vegetation offers little concern about the loss of N. In the case of the application on the surface of the soil, the fertilizer immediately incorporates in soil or directly inject in the soil after dragging from storage tank or pipes (Seadi et al. 2008).

Like any other fertilizer, digestate must be applied during the growing season to ensure the optimum uptake of the plant nutrients and avoid groundwater pollution. Digestate must be integrated into the fertilization plan of the farm in the same way as mineral fertilizers. It must be applied at accurate rates, with equipment that ensures even application throughout the whole fertilized area. The suitable application methods are the same as those used for applying raw, untreated slurry, except for splash plate spreading, which causes pollution and losses of valuable nutrients. Because of the significant pollution caused by splash plate spreading, this method is banned in countries with modern agriculture and environmental protection legislation. The equipment used for applying digestate should minimize the surface area exposed to air and ensure rapid incorporation of digestate into the soil. For these reasons, digestate is best applied with trailing hoses, trailing shoes, or by direct injection into the topsoil. These methods of application minimize ammonia volatilization (Lukehurst et al. 2010).

6.7 Application of fertilizer and potential use of organic fertilizer in Cambodia

The agricultural sector remains a crucial part of economic growth and poverty reduction in Cambodia. Crops contribute largely to farm growth and promote food security. Increasing crop production through the expansion of cultivation areas is not feasible because of population growth. Therefore, future increases in agricultural productivity are expected to come mainly from agricultural intensification, and fertilizer will play a vital role in raising crop yields and sustaining the natural resources of farming land (Theng et al. 2014). The fertilizer industry in Cambodia has evolved rapidly into farm demand, and the overwhelming majority of rice and vegetable farmers use fertilizers. It indicates a positive development of the fertilizer industry and the adoption of fertilizer use in the country. The key constraints affecting fertilizer demand and supplying should be addressed for strengthening trade competition and widening market operations, which, in turn, would bring down prices and increase the quality of products delivered to farmers.

Since 2013, Cambodia has had a chemical fertilizer blending plant in Kandal province. It is a joint venture between Vietnam's Five Star International Ground and Cambodia's Investment and Development Company. This plant is not yet operating at full capacity; therefore, fertilizers are still imported from Vietnam and Thailand, the European Union, or the United States. The supply of fertilizers has increased rapidly in response to agricultural intensification. Among the suppliers, 11 companies import organic fertilizers. Organic fertilizers often cost significantly more than inorganic fertilizers, but the benefits may outweigh these extra costs over time. Organic fertilizers continue to improve the soil long after the plants have taken the nutrients they need. Therefore, the longer the soil is fed with organic fertilizers, the better its composition and texture. On the contrary, while inorganic fertilizer is cheaper in the short term, it adds less to the soil in a long time.

Furthermore, there is a high potential for producing organic fertilizer from commercial biogas plants in Cambodia. Based on BTIC's study, each ton of digestate from liquid pig manure of 4% TS contains 6.7 kg N, 2.8 kg P₂O₅, and 1.9 kg K₂O. As more farm owners and project developers show their interest in biogas plant investment, the enhancement of utilization of organic fertilizer produced through the digestate process can be further studied and commercialized to be used across the country in the future. The use of organic fertilizer will help make farming more economical by reducing mineral fertilizer consumption, protecting the environment (lower GHG than inorganic fertilizer), and improving the public image of the farming and fertilizer industry in Cambodia. It will also benefit the farm owners, the communities, and the country (Möller and Müller 2012).

6.7.1 Nutrient requirement for agriculture in Cambodia

Cambodia has abundant fertile agricultural land, accounting for about 4 million ha in 2012, of which 3 million ha is under rice crop production. Wet season rice occupies about 83 percent (2.5 million ha) of rice farming (MAFF 2013). Soils used for rice production in Cambodia vary largely in their physical and chemical properties. In most rainfed lowlands of Cambodia, soils used for rice cultivation are low in available NPK and organic matter content. Rice is highly variable in its response to fertilizer application, depending on soil type. Therefore, incorrect application of fertilizers may lead to financial or crop losses and environmental damage. Careful consideration must be given to several factors when the rate and timing of fertilizer are being decided. Farmers implicitly consider some of these factors, such as risk associated with erratic

rainfall, when deciding on fertilizer use (Seng et al. 2001). Recommended fertilizer rates (in kg ha⁻¹) for rice vary for the different nutrients: 20 – 120 for N, 4 – 15 for P, and 0 – 33 for K. For example, the NPK need for planting rice at Bakan, Siem Reap province are 75 kg, 13 kg, and 25 kg/ha (Seng et al. 2001). Recommendations are made for each soil type identified in the Cambodian agronomic soil classification system. The economic profitability of fertilizer application in rice was stated by Theng et al. (2014).

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CHAPTER 7 ECONOMIC ASPECTS

Like any industrial construction and investment, a biogas plant's economic assessment and profitability analysis should be done before construction to ensure economically. This chapter covers the general project development roadmaps on economic performance and the main project costs (investment and operation costs). The economic evaluation of typical economic and financial benefits, revenue, payback period, internal rate of return (IRR), and net present value (NPV) are indicated.

7.1 Typical economic and financial benefits

Biogas plants can create economic opportunities in markets where energy costs (electricity grid or diesel) and waste disposal costs are relatively high. The aim of establishing a biogas plant can vary from environmental protection and waste reduction to renewable energy production and can include financial and non-financial objectives. It becomes economically interesting to divert the organic fraction from conventional waste disposal towards AD, producing affordable renewable energy. Local farmers and farmers' organizations, organic waste producers and collectors, municipalities, energy producers, and other involved actors are the usual initiators of biogas projects. It is an opportunity to drive biogas projects from the available substrates in animal farms or agro-industry. However, the farm owners or project developers must control substrates' quantities and compositions to ensure economical (Camirand 2019). It requires a proper plan before starting the biogas project, as indicated in Chapter 4. Important key aspects to be considered include (1) defining and evaluating a business plan and a financing strategy and (2) involving financing companies or financial support from the government in the early stages of the projects. These key aspects ensure the project's long-term success when engaging banks or microfinance institutions for loans.

There are different successful models of setting up a biogas project, depending on the feedstock's availability and the investors' financial capability. Seadi et al. (2008) gave an example of a block diagram showing the main steps of a biogas project. A technical assessment must be done to estimate the biogas production and electricity generation so that revenues can be calculated based on the actual price from the electricity grid or diesel. In addition, the financial assessment allows estimating the payback period and IRR based on the principal investment cost (construction, equipment, operation and maintenance, and others), operating costs, and revenues. For

example, if the IRR rate is higher than 15%, the premise is a good investment, and it is worth continuing the project and moving to the next planning phase. In the next step, it is essential to compare the assumptions with the material reality, which helps get a realistic idea of the biogas plant, the needed space, the actual mass flows, and the total building costs. Finally, the main investment cost and financial analysis will be estimated (Camirand 2019).

7.2 Techno-economic assessment

The techno-economic analysis is the conceptual design of the processes involved in biogas production and utilization, e.g., determination of the required equipment and their sequences, and many other details about the process involved, as shown in Figure 12. The economic assessment and profitability analysis will also be applied (Tao et al. 2013).

The next step is the feasibility study which allows estimating the electricity production in the farms based on the available substrates. The estimated revenue is obtained by multiply the electricity production by the cost of the electricity grid per kW. The total amount of effluent, e.g., total wastewater used, urine, and dung per day in the farm, or only wastewater for organic waste from the agro-industry can be calculated. The evaporation rate of wastewater is considered in calculating the final wastewater, although the rate is low compared to the total water used. Considering the technology selected (lagoon biogas, which is usually more economical), the pond sizes for lagoon and digestate are calculated from the total wastewater per day and HRT (section 4.3.1). The minimum HRT for a wet digester is 30 days; therefore, the minimum lagoon size is at least 30 times the wastewater production per day. The construction cost of the lagoon depends on the materials used (e.g., high density polyethylene (HDPE) material) and types of lagoon technology. The improved lagoon requires inner lining using the same materials as the lagoon cover; therefore, it will add extra cost, while a simple covered lagoon can be constructed without inner lining. However, the lifespan of an improved lagoon is at least 20 years, while it is between 5 – 10 years in the case of a simple covered lagoon, depending on the quality of land, embankment, and compaction.

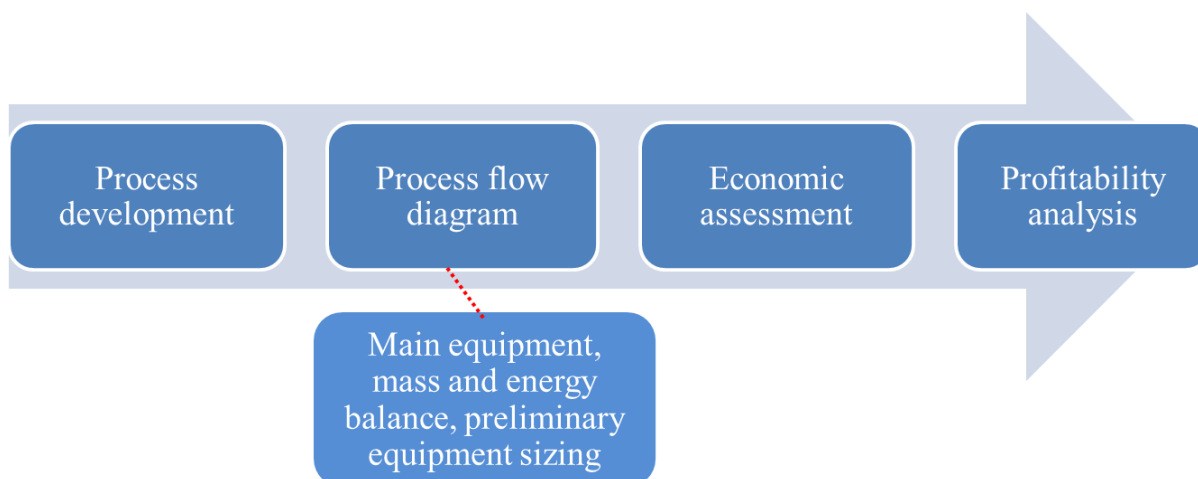


Figure 12 General procedure for techno-economic analysis.

Table 12 indicates a technical assessment of pig farm A in Cambodia, which BTIC biogas experts conducted. The electricity generation can meet 70% of the annual energy demand for the evaporative cooling system or other equipment such as pumping, lighting, and others on the farm. Based on the electricity production per day and grid electricity price of 0.185 USD/kWh, the estimated annual revenue is approximately 42,000 USD. The minimum lagoon size is around 9,150 m³, and the cost assessment of the lagoon is 79,000 USD which is based on the quotation from biogas suppliers (costs of materials used) and the contractor (cost of construction).

Table 12 Estimation of electric production and lagoon size from the total wastewater in farm A in Kampong Speu Province, Cambodia.

Source	Unit	Average
Water	t/d	216

Dung (fresh)	t/d	10.8
Urine	t/d	18.8
Evaporation	t/d	4.5
Total wastewater	t/d	240
DM content	%	0.9
Total DM	t/d	2.16
Biogas	Nm ³ /d	713
Electricity production	kWh/d	1069
Electricity demand	kWh/d	1125
Lagoon size	m ³	9150

7.3 Financial analysis

The financial analysis is conducted to calculate the total budget for the biogas project, payback period, and the investment's internal rate of return (IRR). The IRR is the profitability of the potential investment. The payback period is when the biogas project benefits based on the total investment cost and net cash flow. The net cash flow is proportional to the total cash-in (revenue and residual equipment value) minus the total cash-out (the investment on the equipment and O&M costs). The total budget depends on the investment and operation costs, as indicated in Figure 13. The investment cost on equipment, construction, and others must pay in the year of the biogas investment. Operating expenses on staff salaries and maintenance (annually charge 2 – 30%), etc., can be paid monthly, annually, and few yearly (depending on the life span of equipment), respectively. However, all items in the lists might not be applied to all farms in Cambodia. The farm owners or project developers should consult with a biogas expert and an experienced biogas company to conduct financial feasibility and calculate financial investment (Karellas et al. 2010). In addition, the concrete financial situation, such as evaluating a business plan, a financing strategy, and the advantages and risks of the investment, must be considered. The farm owners should seek financial or non-financial incentives for establishing the biogas plant. In case that they cannot self-finance, banks or external financiers must be involved. However, there are no financial institutions that finance biogas projects in Cambodia. There is still an ongoing discussion between BTIC, NBP, and stakeholders to provide the market size of the

commercial biogas in Cambodia to attract banks and microfinance institutions in developing loans for biogas projects. For example, investors should give information on the project features (potential of biogas production and profitability) or business plans of commercial biogas plants to ensure that the borrowers could pay back the loan.

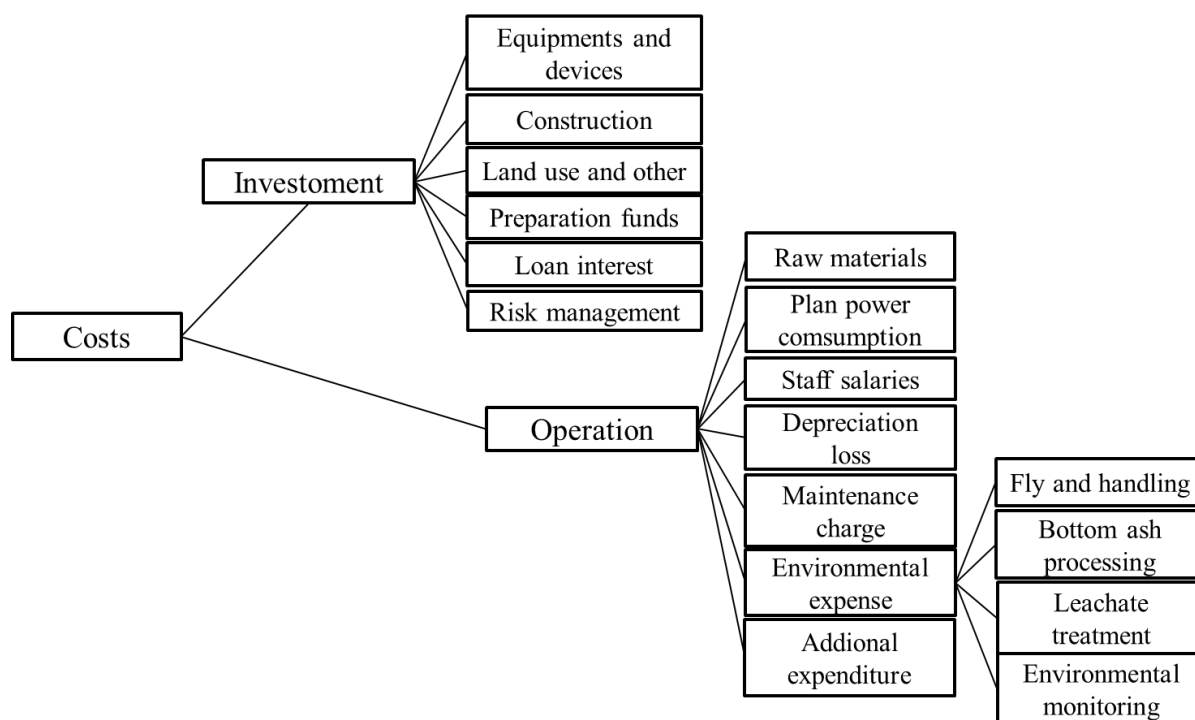


Figure 13 Investment and operation costs of biogas plant (Zhao et al. 2016).

7.3.1 Financial Feasibility

Biogas plants are usually financed from the owner's resources, credit, and public promotion. Some farms have installed biogas plants with grant support from UNIDO under the GEF-5 project. Farm owners could get incentives up to 20–25% of the total investment or a max of 45,000 USD per project, depending on the scale and type of project. However, this support grant had a limited budget. The installation of the systems was only supported for proposals that have a positive feasibility study available and fulfill the eligibility criteria at the time of contract closure with UNIDO.

A financial feasibility study convinces investors and creditors of the technical feasibility, economy, environmental compatibility, and general creditworthiness (Deublein and Steinhauser 2010). The success of the project depends on some factors that can be controlled and influenced by strategic decisions concerning investment and operational costs, as stated in Figure 13 (Zhao et al. 2016). Therefore, the following questions must be answered:

- Will the plant work economically, based on a turnover and a profit projection with the cost-benefit calculation?
- Is there a detailed plan for the financing (own resources, guarantees, and collateral)?
- How to get a loan with low interest from banks or microfinance institutions for a biogas plant project?
- Is annual income from biogas investment sufficient to cover the operation costs and loan repayment (in the case of the farms' owner loan from the Bank)?
- Is the overall risk to the biogas project clear and acceptable?

A financial feasibility assessment must be conducted to find in detail the annual cash flows in the project. It is a critical step in assessing the practicality of a proposed project. The financing options depend significantly on local conditions and the situation of the project initiator, so there are no universal guidelines for this (Seadi et al. 2008). In addition, the economic feasibility and efficiency should be investigated to find the hot spots of cost accounting. Currency outflows for initial construction and installation and maintenance costs and other operating costs should be considered. Moreover, both actual and potential monetary inflows for the substitute benefits of biogas products should be listed. It would be crucial to construct an economic framework to understand the money flows and find the key to optimize economic feasibility (Chen et al. 2017).

In the case of conducting the analysis, a few software have been developed. COMFAR III EXPERT (Computer Model for Feasibility Analysis and Reporting) is among the most promising ones. UNIDO has developed this tool based on the experience, recommendations, comments, and needs of more than 7000 users in 160 countries. Since its release, the software has been upgraded yearly to meet the technical developments and users' requests (Ghodrat et al. 2018).

In Cambodia, on the other hand, BTIC offers consultancy services on the financial feasibility and investment costs to farm owners and investors, and BTIC can answer those questions mentioned above. BTIC also helps on (1) technical assessment and performance improvement of biogas system; (2) development of a bankable proposal and access to credit; (3) assistance investors on preparing a proposal for the grant if it is available; (4) supporting in Engineering, Procurement, and Construction Management (EPCM); and (5) training related to commercial biogas for stakeholders such as safety, operation, and maintenance of commercial biogas systems, construction and commissioning, etc. (<http://btic-rua.org/>). As mentioned in section 2.4, M's pig

farm successfully operated the first commercial biogas plant that received technical support from BTIC. In addition, financial feasibility assessments were conducted at more than 30 farms and agro-industries. The following section will discuss the calculation of financial investment cost, cash flow, and economic indicators of pig farm A conducted by BTIC.

7.3.2 Calculation of Financial investment cost

The calculations in this section are formulated based on the experience of biogas experts from BTIC in Cambodia. The investment costs concern equipment such as lagoon (including materials and construction costs), genset, gas treatment, flow meter & gas flare, tubing and cabling, equipment transportation and installation, commissioning, and operator training. The costs for equipment and installation are based on a quotation from equipment suppliers, and costs for equipment housing are estimated. In addition, estimates of equipment-related costs such as O&M costs and equipment depreciation are indicated in Table 13. The cost of the lagoon has a significant impact on the total capital investment cost. As wastewater lagoon is a part of normal farm operations, the entire investment cost can be reduced by more than 30%. Table 13 Overview of the investment cost of farm A in Cambodia.

Investment costs	Price (USD)	O&M (%)	Lifespan (year)	Depreciation (USD)
Lagoon	79,000	2	20	3,950
Generator house	10,000	2	20	500
Gas treatment	5,000	30	10	600
Genset (second hand)	32,000	15	4	8,000
Flow meter	980	5	5	196
Manual flare	450	5	5	90
Tubing and cabling	1,000	5	10	100
Transportation	1,500			
Installation costs	5,000		10	500
Sub-total	134,930			13,836
Total project budget	148,423			15,185

7.3.3 Cash flow and financial indicators

Table 14 indicates cash flow **Error! Reference source not found.** for 10 years period in the whole production scenario. The expense of 148,423 USD in the first year (year 0) is the total investment cost. It's a long leap from lifespan to re-investments to the same net cash flows. The calculated net annual savings (revenue – O&M annual) is around 35,857 USD. The cumulative cash balance after 10 years is 189,212 USD, which is calculated from the net annual cash flows and the remained 44,500 USD from residual equipment values. With a discount rate of 14%, the project net present value (NPV) is 15,992 USD.

Financial indicators can be calculated from the annual cash flows. The IRR is 16.9%, which is slightly above the chosen depreciation rate of 14%. The payback period is 4 years which is long for a commercial biogas project. However, because the farm owner gets an incentive of 24,000 USD from UNIDO to support the biogas investment, the payback period is down to 3.4 years. IRR and NPV are 21.9% and 37,045 USD, respectively.

Table 14 Cash flow of the investment.

	Years				
	0	1	4	5	8
Cash-out					
Investments	148,423		32,000	1,430	32,000
O&M costs		6,101	6,101	6,101	6,101
Total cash outflow	148,423	6,101	38,101	7,531	38,101
Cash-in					
Electricity bill savings		41,958	41,958	41,958	41,958
Total cash inflow	-	41,958	41,958	41,958	41,958
Net Cash flow	-148,423	35,856	3,856	34,426	3,856

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CHAPTER 8: RISK ASSESSMENT AND SAFETY OF BIOGAS PROJECT

This chapter presents an overview of qualitative risk analysis and assessment of biogas projects. Some hazard identifications on biogas production and upgrading and risk estimation are given. The safety of biogas projects, including safety systems and safety guidelines, and documents for preventing risks and hazards, is also discussed.

8.1 Introduction to risk assessment

Biogas plants should undergo a formal risk assessment consisting of the systematic identification of risks and descriptions of the technical and non-technical measures undertaken to control the identified risks. Anaerobic digestion is a chemical process with all the associated risks, e.g., interaction with other operating plants or contractors, hazardous areas, flammable gas, fire and explosion, hazardous substances, pressure systems, gas handling, gas storage, and use of un-odorized gas. In addition, human failures in operating the biogas system are a key determinant in risk control, centered around procedures and maintenance issues (Inspectorate 2018).

Risk assessments allow to control the issues from hazards and risks of biogas plant such as (1) What potential hazards are present?, (2) What potential causes and consequences are associated with those hazards?, (3) How significant are the potential impacts?, (4) What effects might flow from these hazards?, (5) What is the likely risk in qualitative terms on a range of risk receptors such as people, the plant itself or the environment?; and (6) What potential design guidelines and system controls are needed to maintain risk to as low as reasonably possible? Therefore, thorough safety assessments must be carried out at each project stage from design to installation, commissioning, implementation, and operation. The standard hazard identification processes are used to elicit and document the hazards and their potential for harm to people, plant facilities, and the environment. Taking proper precautions and safety measurements contribute to ensuring a safe operation of the plant. Application of inherently safer design practice can help bring risks to as low as reasonably practicable through the complete elimination of hazards. It should be the aim of all designs and operational considerations around biogas production and use (Seadi et al. 2008).

8.1.1 Overview of qualitative risk analysis and assessment

A qualitative assessment is made on biogas facilities' individual and overall risks and hazards impacts, which considers the identified hazards arising from the

release of biogas from containment, either at the covered anaerobic lagoons (CALs) or within the gas transmission system or end-user facilities. It gives clear hazard identification and consequence analysis that affect distances for the events, given the location of the operation. Many events from gas releases that generate fires have localized effects. The failure rates leading to loss of containment in gas transmission systems are meager, particularly for commercial piping and equipment such as valves and blowers. However, the effect of human failures can be significant, as key contributors to loss of containment, either at the system's design phase or through poor training and poor procedural practice. These human factors must be expressly considered and managed within a facility to minimize the hazard potential (Dow 1994).

There are some more significant biogas releases from the CALs that could, under certain restrictive circumstances, affect distances of more than 50 m. This type of event might have some implications for facilities located close to other operations or land uses. For specific plant locations and surrounding sensitive land uses, a quantified risk assessment would be required to assess the imposed risks and adequacy of the proposed design and operations (AMPC 2016).

On the other hand, the growing use of biogas to generate electricity on-site has led to generator sets, usually installed in enclosed structures for noise control and security reasons. It poses a unique risk of explosion of released gas within the enclosure and amplification of blast pressure compared to open systems. There are potentially more severe impacts on-site in the case of large releases of gas from CALs, and the possibility of explosion impacts from enclosed space ignition of biogas in generator set installations. Multiple failures can occur in gas detection and ventilation systems that permit explosive atmospheres to form within these facilities. The physical location of the facility on the site is important to mitigate possible impacts from explosions. Where appropriate, the use of open areas is an inherently safer design option than the covered areas. Besides, ventilation systems, interlocks, and gas detection mean that initial events can often not propagate to an explosive situation. It is worth considering the use of open structures to avoid explosive overpressures if systems fail. Other minor events are possible, but again the effects are small and localized to the operation. The propagation of events must be promptly addressed, as escalation could generate severe outcomes on the site (Hughes 2006).

8.1.2 Hazard identification and risk estimation

This section analyzes the possible physical effects of events occurring to provide information on impact zones affecting people, the environment, and the associated biogas plant. The risks related to people on-site consider a probability of exposure people to the hazardous event and gas ignition when flammable gas releases were involved. The potential impact both on-site and off-site is primarily related to the hazardous properties of the biogas and the release locations. Since biogas consists mainly of CH₄, CO₂, H₂S, and other trace compounds, it is flammable and potentially explosive. These types of events within the biogas system need control, using both installed safety systems and physical separation of plants from vulnerable resources. A biogas system is often composed of (1) Influent feed system, (2) CALs, (3) Biogas transfer system, (4) Flare systems, and (5) Biogas utilization systems. Off-site individual risks would usually assume constant exposure to any risks generated from biogas operations. However, given the general location of biogas facilities and the use of separation distances between biogas facilities and sensitive land uses, the risks to the public are likely low. The estimation of risk impacts of the above biogas systems on hazard, possible causes, possible consequences, protection measurement, and residual risks to people, environment, and assets have been listed in AMPC (2016).

The key hazards related to gas releases, possible fires, and explosions are considered by applying consequence analysis, where predictive models were used to estimate the impact of such events. For example, the consequence analyses consider dangerous phenomena such as fires associated with cover failures and other loss of containment events from equipment items. It also covers potential open flammable cloud flash fires and/or explosions by biogas releases from (1) CAL cover, subsequent jet fires (JF) and flash fire (FF), (2) transmission systems (JF and FF), (3) generator facility such vapor cloud explosion (VCE) and JF, and (4) release of biogas and downwind impacts of H₂S. The threshold values for damage distance evaluation can be found in Tugnoli and Cozzani (2007).

Analysis of H₂S releases indicates that on-site and off-site impacts could occur under a range of release scenarios. For example, the loss of containment of biogas containing large amounts of H₂S beyond 0.2% (2000 ppm) can cause significant health risks, especially at night, where effect distances can be greater than 500 m from the release point. Therefore, these scenarios require the application of inherently safer design principles and, where necessary, the implementation of independent protection

layers, including emergency response procedures, to be in place to eliminate or mitigate the loss of containment impacts. The sequence estimates show that there is little potential for major off-site impacts from fires and explosions. Hence the risks beyond the boundary from these events are low. It is particularly the case given the general siting of these operations away from residential areas. The basic assumptions used in predicting the downwind concentration of H₂S was indicated in the literature (AMPC 2016).

8.1.3 Risk assessment on biogas production and upgrading

The risks associated with biogas production and upgrading to biomethane are investigated step by step, as illustrated in Figure 14. The first step involves identifying the equipment present in the process and the related operative conditions such as pressure, temperature, involved substance, and hold-up. After that, a set of credible critical events referred to as Losses of Containment (LOCs) such as a small leak, pipe leak, and rupture is assigned to each Process Unit. A set of possible loss of containments for each equipment unit can be potentially dangerous phenomena such as gas fire and explosion.

The impact of such phenomena was assessed in terms of damage distances and hazard indexes. The damage distances are defined as the maximum distance where the physical effect of a scenario such as thermal radiation, overpressure, or toxic concentration reaches the threshold value. The damage distance can be calculated using consequence analysis models based on the LOC characterization. Several models and commercial software tools are available in the literature for consequence analysis (Haimes 2009) (Aven 2011). The calculation of the equipment hazard indexes requires the estimation of a parameter representing the severity of each scenario that the identified LOC events may trigger. The damage distances corresponding to a given effect threshold were calculated to obtain a homogeneous severity parameter of each scenario. Different types of physical effects are compared in the analysis. (Scarponi et al. 2015).

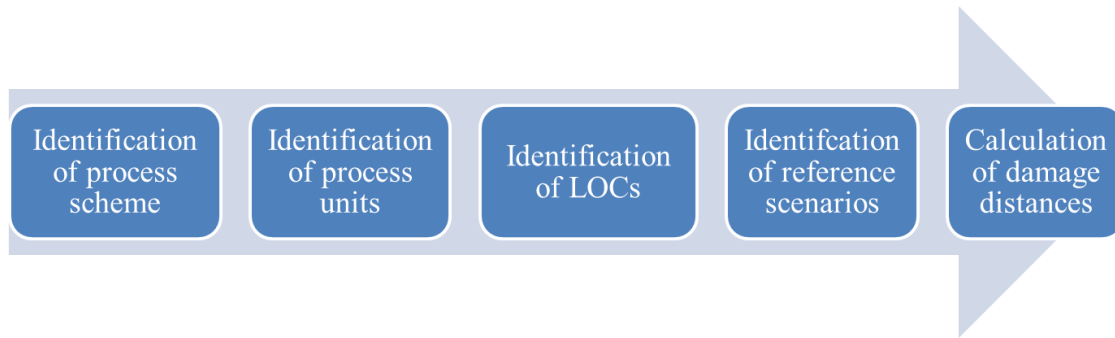


Figure 14 Schematic representation of the steps of the methodology used for the risk assessment (Scarponi et al. 2015).

8.2 Health and safety issues

The target for biogas plant is to ensure the highest possible level of safety for humans and the environment. Safety regulations must be understood by those who are expected to observe them and that they can be applied in the applicable economic framework. Some hazards can occur in connection with the mechanical operation of biogas plants or the uncontrolled escape of biogas. The relevant regulations for device and product safety and health and safety must be observed during the construction and operation of a biogas plant (Wellinger et al. 2013). For health and safety reasons, all risks and hazards of biogas are considered at all phases of a biogas project development. The construction and operation of a biogas plant, including biogas production and upgrading, face typical health and safety issues. It is due to the number of risks and hazards, such as biogas fire and explosion, LOCs to the atmospheres, and other hazards, as shown in Figure 15. The most critical safety and mechanical issues are fire and explosion, H_2S and NH_3 poisoning, asphyxiation, and diseases (Peters et al. 2003).



Figure 15 Hazards of the biogas plant.

8.2.1 Fire and explosion hazards

In combination with air (oxygen) and an ignition source, combined gas can form an explosive gas mixture under certain conditions, depending on CH_4 content. Besides, excess H_2S and NH_3 are potentially explosive. The risk of fire and explosion is particularly high close to digesters and gas reservoirs. It can also occur because of a gas leak, the creation of an explosive zone, welding, clogged or frozen pipes, or others. Therefore, around the biogas digesters, gas pipes, CHP units, gas flares, and gas storage tanks, collectively called Ex-Zones. All types of safety measures related to explosions should be considered, including installing and using acceptable devices (Westenbroek and Martin 2019).

8.2.2 Risk of asphyxiation and chemical and disease hazards

Biogas generation, transportation, and flaring can lead to oxygen-deficient atmospheres. The biogas accumulation in a confined space can significantly reduce the level of oxygen (anoxia) and result in poisoning or asphyxiation symptoms, even death. The minimum regulatory oxygen content is 19%. The asphyxiants that are typical constituents of biogas are CO_2 and CH_4 . Due to their toxicological properties, NH_3 , H_2S , or CO_2 expose operators to safety hazards. Someone exposed to H_2S concentrations of over 50 ppm can get serious injuries, e.g., exposure to concentrations higher than 1,000 ppm cause immediate death. Such concentrations also cause pipes or steel tanks corrosion or breakdowns of the biogas engine. The substrates in biogas plants may contain pathogens, such as bacteria, viruses, and parasites that may cause disease in man, animals, or plants. This fear is not at all unfounded at first sight. The

general public often discusses the risk of pathogenic germs spreading with the digestion residue in fields (Wellinger et al. 2013).

It is essential to monitor gas regularly, e.g., biogas measurement, gas leakage, pipes, and operation and maintenance of equipment at different locations for the efficient and proper functioning of the process and to reduce the risks and hazards. In addition, it is essential to install safety systems and provide safety guidelines and documentation in the biogas plant (Hofmann 2016).

8.3 Safety systems

According to ATEX classification on explosion-safe products, explosion-proof equipment, electrical service, and non-sparking tools should be installed around digesters and biogas storage. There must be no smoking near the digester or related biogas lines. Large engines and electric generators must be suitable for the environment so a spark will not ignite the gas (Westenbroek and Martin 2019). The key safety systems typically deployed for biogas generation and use such as:

1. Pressure relief on CAL covers via hydraulic dip legs cover spears or weighted flap valves.
2. Moisture knock-out pots to ensure no significant carry-over of liquids into the biogas transport system.
3. In-line methane analyzers to continuously read methane content.
4. Deployment of methane gas sensors as part of the instrumented safety system for power generation.
5. Ventilation of enclosed spaces occupying engine-generator sets.
6. Use of flare systems to burn unwanted biogas and for over-pressure relief of the transport systems.
7. Biogas flaring systems: burner management with safety interlocks (AMPC 2016).

8.4 Safety guidelines and documents

Operating staff and owners need proper training from biogas experts to ensure that they can understand the operating instructions for a biogas system in regular operation and are aware of biogas hazards and safety in the biogas plant. They must determine, evaluate, and minimize the dangers. They must consider the acquired knowledge by setting protocols describing response in case of accidents and providing

safety training to the biogas operators and owners. On the other hand, the operators need to monitor biogas systems: (1) daily (monitor digester temperature, record gas meter reading, check the motor oil level and airflow injected for desulfurization, etc.); (2) weekly (check fill level in the overpressure and under-pressure protectors, inspect the motor and lines, and check gas magnet valve for function and contamination); (3) monthly (actuate all scrapers to ensure no struck and remove oil deposits in the CHP unit); (4) twice a year (check ventilation, inspect the electrical systems for damage, and check the function of gas sensor and fire detector); (5) annually check gas-carrying system parts for damage and corrosion and calibrate the gas sensor), and (6) check the fire extinguishers in every 2 years. The details of safety guidelines can be found in this report (Findeisen 2015). On the other hand, it requires keeping the documents such as manual/guidelines and O&M available in the biogas plant and labels the biogas hazards, safety, and protection as shown in Figure 16 (Westenbroek and Martin 2019).

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AMPC (2016) Appendix 2 : Hazard and Risk Assessment - Biogas Systems.

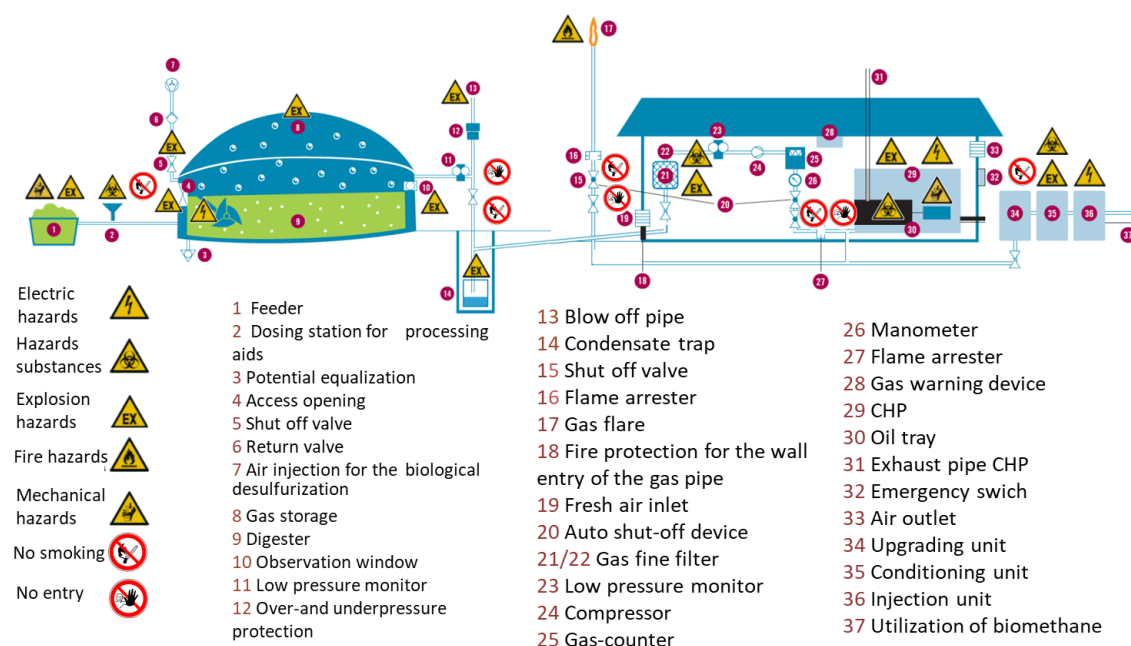


Figure 16 Overview of hazards and safety systems in biogas production and utilization (Westenbroek and Martin 2019).

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CHAPTER 9 LEGAL, ENVIRONMENTAL, AND SOCIAL ASPECTS OF BIOGAS PROJECTS

This chapter describes the legal requirements and documents that investors need for their investment in a biogas plant. Legal frameworks and guidelines for the development of biogas plant in Cambodia are discussed. The environmental and social aspects of the biogas project are also discussed.

9.1 General legal terms and requirements for biogas project

The procedure, criteria, and documentation needed to get a biogas plant building permit differs from one country. The investor must document the project's compliance with national legislation concerning handling and recycling of manure and organic wastes, emissions regulations (exhaust, noise, and odors emission), impact on groundwater, protection of landscape, work safety, buildings safety, etc. It is very important to contact local government authorities in an early stage of the project, provide them first-hand information, and require help with the permitting process and project implementation (Wellinger et al. 2013). Fulfilling essential safety issues and stipulating straightforward prevention, protection, and damage control measures are conditions for obtaining the building permit (Seadi et al. 2008). When permits for plants are granted, it needs to be ensured that the permit applicant has a sufficient land area at its disposal for spreading nutrient-rich digestates. Involving an experienced planning company in getting the building permit can be helpful or necessary, depending on the local situation. For instance, they might know how long it takes for permitting procedures to build and operate a biogas plant (Camirand 2019).

In addition, legislation (regulation and permission) and guidelines for biogas projects (before and during the operation) below those investors need to follow:

- Local regulation regarding anaerobic digestion
- Permitting authority from the environmental and health protection agency.
- Safety of products, services, and industrial activities.
- Biogas building permits from the authority.
- Business plan and risk assessment.
- Available professional technical biogas in-house for O&M.
- Local restrictions on selling electricity to the grid or community when electric production is higher than the demand. However, most of the existing

biogas systems in Cambodia cover around 80% of the total electricity demand in their farm.

- Feedstock description and declaration (an official document that should be archived at the biogas plant).
- All feedstock types should be analyzed and tested regularly to maintain quality standards and adhere to the legal requirements for feedstock quality.
- Legislation and the authorities ensure that nutrients in the digestate spread to cultivated fields are fully accounted for and monitored.
- Waste reduction and recycling regulation.
- Work Health and Safety protection.

9.1.1 Legal frameworks and policy for the development of biogas plant in Cambodia

Legal frameworks: Unlike other countries where the legislation for developing biogas plants already exists, there is a lack of legal terms and frameworks on the procedure and standard requirements for registration for investing in this technology in Cambodia. Currently, suppose investors, farm owners, or project developers are planning a biogas project. In that case, it is recommended to contact BTIC center or NBP for helping all the procedures, such as Engineering, Procurement and Construction Management (EPCM), economic assessment, and assisting the application for incentives from the government NGOs or development partners if it is available. They also provide technical and consulting services and documentation on biogas regulation and guidelines of biogas safety and O&M. However, there is a need for biogas legislation and policies and roadmaps to support further and effectively implement biogas plants in Cambodia in the future. In this regard, governments can support biogas technology use by forming regulations that favor the sustainability of biogas plants. In addition, funds from development partners and the government constitute a significant resource to support NBP and BTIC in the long-term sustainability of biodigester development. Creating a favorable climate for biogas dissemination depends almost always on a whole range of decision-makers (MAFF 2016).

Biodigester policy on biogas plant: Recently, MAFF created a national technical working group to provide technical support to biogas projects and revise the existing documentation on biodigester development policy and legal framework (2021 – 2030). MAFF will establish a National Advisory Committee for effective coordination of the implementation of the biodigester development policy. In addition,

a Provincial-municipal Technical Working group will be created to coordinate and implement activities at a local level, contributing to the implementation of biogas development policy (MAFF 2016). On the other hand, biogas programs should attempt to lobby for biogas at various entry points of the government system (cooperation among ministries) simultaneously. For example:

- 1) MEF: decision on subsidies and tax waivers for biogas investors and users.
- 2) MOE: propose laws regarding the feeding of biogas-produced electricity into the farms or community.
- 3) MAFF: prepare a curriculum of biogas training to extension officers, agricultural colleges, and agriculture and livestock investors.

Scaling-up of Renewable Energy Technologies (S-RET) project promoted renewable energies (biogas, solar) for application in agriculture products such as solar pumping, solar incubator, etc. The project phase has been completed; however, the donor IFAD (International Fund for Agricultural Development) considers the project's second phase.

9.2 Environmental aspects

Biogas is a form of renewable energy and is considered a green solution is transforming organic residues and wastes into valuable products such as electricity, heat, biofuel, and organic fertilizer. However, if a biogas plant is not well located, designed, and operated, it can harm the environment and surrounding residence and community. Following the environmental regulations and guidelines, e.g., where to place biogas plants and recommended distance to the nearest neighbor in the city area or communities in rural areas, biogas storage and fertilizer use, can avoid environmental issues (Hus 2020).

9.2.1 Environment regulation

Environmental regulations for factories are provided under Instruction/Sechkdey Nainoam No. 87 on Factory Hazardous Waste Management, including standards for the following: (1) desludging and sludge storage; (2) prohibition of disposal of factory sludge with household waste; (3) prohibition of discharging of sludge to water bodies; (4) the need for permission to transport sludge; (5) managing hazardous waste and persistent organic pollutants, environmental quality and effluent standards, and (6) water emissions standards to be released into the environment, including requirements to treat waste products such that emissions standards are met

(Lord and Leang 2021). Prakas No 387 Br.KB, MOE launches standards of the number of toxic chemicals or hazardous substances contained in hazardous wastes allowed to be disposed of in sanitary landfills and soils (MOE 2015). Air and noise pollution standards are provided under Sub-decree #42 under-declaration/Prakas No. 83 (Government 1999). According to Prakas No 549, commercial animal farms are recommended to manage their waste correctly by converting it into biogas to reduce environmental impact from animal wastes (MAFF 2018). However, the environmental regulations and policies for the biogas industry in Cambodia are not set. MAFF, MoE, and MME should work together to implement the existing regulations and prepare new regulations on environmental pollution control (water, air, and soil), type of feedstocks, and overall environmental impact assessment (EIA) on biogas plants. In particular, the regulations should also apply to the utilization of digestate as organic fertilizers.

Lesson learned from Europe: The environmental regulations on biogas development in other countries, especially European countries where biogas plants have existed for decades, stipulate that biogas investors must apply for a permit. The environmental permits on biogas plants are based on the law of Environmental Protection. Professional handling of waste triggers the environmental license of biogas plants, e.g., large-scale animal farming needs an environmental permit, but when biomass waste of own farm is treated, the permit can be integrated into the environmental license of the farm. Similarly, farm owners need to submit a document containing a plan for constructing the biogas system to get licenses for biogas investment.

The standard requirements include reception and storage of manure and other types of biomasses, anaerobic digestion, separation of digestate and storage of the separated biomasses and upgrading, and storage of biogas. The regulated environmental issues include air emissions (odor, H_2S , dust, and NH_3), noise, and soil and groundwater or surface water pollution. The permitting authority shall use the standard requirements as a basis for the permit. Still, it is possible to set other requirements if they are not balanced between environmental effect and economics (European Parliament and Council 2009). Different standards are applicable for constructing a biogas plant and raw materials and products depending on the feedstocks produced and plant operations. Below are some requirements for other feedstocks and the use of digester as organic fertilizer.

Animal manure feedstocks: The animal by-products regulation generally states the terms for preventing the spread of diseases within the processes of moving materials of animal origin not intended for human consumption. It says that treatment in biogas plants can be suitable for several such products.

Organic Fertilizers: open digestate storage is banned to prevent methane emissions and regulating digestate spreading onto land to minimize emissions of ammonia and related environmental impacts (Fusi et al. 2016). Organic fertilizer products placed in the market must be investigated to ensure that they are safe in marking, packaging, transport, storage, use, good quality, and suitable for plant production (European Parliament and Council 2009).

9.2.2 Environment impacts of biogas production and utilization

Using heat and electricity from biogas would significantly improve environmental sustainability, reduce global warming, and deplete abiotic resources and the ozone layer. Grope et al. (2019) indicated that a 1 MWe biogas plant could reduce approximately 7,000 tons of CO₂ emission per year compared to fossil fuels' electricity production. However, the social acceptance of biogas is often hampered by environmental and health concerns. Biogas, generated by the biogas project, can significantly contribute to abate GHG emissions, namely CO₂, CH₄, NH₃, and N₂O. The environmental impact induced by feedstock, biogas upgrading, digestate storage and treatment, and the final use of digestate is critically discussed. Attention must be paid to undesired emissions of CH₄ and N₂O. Among all the gaseous pollutants considered indirect emission from biogas combustion, nitrogen oxides (NO_x) level was the worst environmental concern (Paolini et al. 2018).

Impact of feedstocks and biogas upgrading: The effect of a biogas plant on GHG emission is heavily influenced by feedstock storage. Most N₂O can be lessened when closed storage is used for manure. Emissions from uncovered biomass storage are also the primary NH₃ source along the biogas production chain (Sommer 1997). On the other hand, feedstocks from MSW highly influence the impact of the whole plant as they are: (1) the features of degradation of the fermentable fraction; (2) the collection efficiency of gas streams released by biological operations; (3) the abatement effectiveness of collected pollutants; and (4) NO_x emission rate from biogas combustion (Beylot et al. 2015).

Using biomethane as an alternative to fossil fuel generally improves local air quality and reduces GHG emissions. However, CH₄ losses can affect the sustainability

of the whole process. The equivalent CO₂ saving raises considerably if CH₄ slip is limited to 0.05%, but the process is no longer sustainable when methane losses reach 4% (Paolini et al. 2018).

Impact of digestate storage and utilization: Utilization of digestate as organic fertilizer can release nitrogen and ammonia emissions into the atmosphere and groundwater, which has long-term effects on sustainability in terms of soil fertility and environmental impact. Uncovered digestate storage has been identified as the main ammonia emission source. Proper management of digestate can mitigate its environmental impact by reducing ammonia emission rates. The importance of a gas-tight tank for digestate storage can reduce GHG emissions by up to 36.5% (Battini et al. 2014). The main critical issue in the final use of digestate is nitrogen release into the environment, which can be reduced by applying best practices for preserving soil quality. However, managing nitrogen dosage is difficult because of the feedstock variability (Paolini et al. 2018).

N₂O and CH₄ emissions from digestate utilization are not critical in comparison to those of untreated biomass and fresh slurry manure. In particular, adding digestate to paddy increases the CH₄ emission rate from 17 to 30 g m⁻², but no significant effect is observed for N₂O (Win et al. 2014). Regarding pesticides, heavy metals, and harmful microorganisms in the digestate are generally considered to pose a low risk of food chain contamination. However, the soil burden of persistent organic pollutants caused using digestate still needs to be fully assessed (Suominen et al. 2014). It is important to note that fugitive emissions from digestate storage are generally more important than those released by its use into the soil (Buratti et al. 2013).

9.3 Social aspects

Like the legislation and environmental aspects, social regulation and impacts of the biogas plant site must be integrated into the project approach when planning a biogas installation. It is strongly associated with land use and social conditions related to community empowerment. It is important to determine whether social conditions are suitable for biogas plant project implementation. The following information should be considered: (1) social needs (heat, electricity, and organic fertilizers) and concerns (odor, waste disposal problems, etc.) and (2) the location of the biogas plant. Determining heat, electricity, and digestate requirements are needed (Pandyaswargo et al. 2019). Besides, people are very concerned about impacts such as odor, noise, and

undesired landscape changes, and the appearance of bad examples in the media amplifies these fears. Determining whether a location is rural or urban is essential in estimating the appropriate scale and technologies for a project. In particular, zone conformity and distances to buildings, forests, rivers, lakes, or sources must carefully measure to prevent the risk of biogas production. Therefore, early contact with the municipality and the regional permission authorities can be helpful and prevent conflicts with community and local businesses, e.g., electricity distributors (Wellinger et al. 2013).

9.3.1 Social conditions and gender consideration

Social conditions should be identified, and authorities should strive to address all regulations related to the biogas plant. Regarding social factors, the farmers' education level plays a vital role in adopting biogas plants, concerning their ability to foresee the benefits and operate the biogas plant. However, the farmers in Cambodia have limited knowledge of and information about biogas. Therefore, local political governance is regarded as an essential factor in disseminating, training and implementing biogas energy policies at a local level (Yang et al. 2021).

On the other hand, social challenges identify the use of local labor, guaranteeing safety, ease of operations, aesthetic considerations, and consideration of ethical barriers. Working conditions should be improved by strengthening the regulations regarding the casual daily laborer, such as improvements in wage and benefits, health and safety standards, and rights for collective bargaining and biogas operators. Guaranteeing safety is always a central concern when new technologies are implemented. By equipping operators with technical maintenance capacities, such problems can be addressed, and the presence of a similar facility in each area can improve the acceptability of adopted technologies (Chingono and Mbohwa 2016).

The involvement of local labor is more accessible on technical assistance and affordable services. Social regulations for the division of labor should follow gender considerations (a division of labor between sexes). The sustainability strategy includes monitoring, evaluation, and promoting gender equality and the empowerment of women (GEEW) in participation in biogas training (Mohanty 2017). The existing social regulations on the division of labor represent a framework that is difficult to determine. Different models should be considered according to the standing of women in society. Women should be involved in decision-making committees. For example, when there are problems with the plant, the women can be a stabilizing element. As they are more

affected by malfunctioning of the plant, they are more interested than men in, e.g., a well-functioning repair service. It indicates that GEEW has a significant positive impact on sustained economic growth and sustainable industrial development, which are drivers of poverty reduction, social integration, and environmental sustainability (UNIDO 2015b).

9.3.2 Social impacts

The development of biogas technology is a vital component of alternative rural energy programs, whose potential is yet to be exploited. Biogas plants can have many positive social effects by creating employment for appropriately trained students, unemployed youth, and entrepreneurs through regular follow-up service, maintenance, and repairs. Coordination of production and use of biogas, fertilizer, and pollution control can optimize the promotion and development of agriculture and animal husbandry in rural areas. Biogas technology creates new workplaces and employment in communities. Generally, there is an employment of skilled, semi-skilled, and unskilled persons in the building and construction of the plant. It improves living facilities in villages, thus less migration to the city. The investment in biogas plants provides additional income-earning activities from improved yields of agriculture products using organic fertilizers. It gives energy self-sufficiency to the farms or internal local community (Omer 2015).

Although biogas plants implement new solutions and technologies of renewable energy in the market with good protection of the environment and climate, they also have some drawbacks. Concerning the negative impacts on the well-being of local communities, the government must take measures to fully recognize and protect the rights of local communities that might be threatened by the expansion of biogas production and its environmental hazards and implications (Chingono and Mbohwa 2016). Moreover, odor and other waste management-related social problems must be identified. Odor prevention methods may be introduced when problems are anticipated or exist in each area. Those who handle waste should also be identified to determine which stakeholders to target when socialized waste separation systems (Pandyaswargo et al. 2019).

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