University of South-Eastern Norway

www.usn.no

FMH606 Master's Thesis 2023

Engineering Course (Master) – Exchange Student

Evaluate the Potential Technologies for small-scale biogas treating agricultural waste in Sri Lanka

Fathima Aroosa

Faculty of Technology, Natural sciences and Maritime Sciences

Campus Porsgrunn

University of South-Eastern Norway

www.usn.no

Course: FMH606 Master's Thesis, 2023

Title: Evaluate the potential Technologies for small-scale biogas treating agricultural waste in Sri Lanka.

Number of pages: 56

Keywords: Agricultural waste, biogas, small-scale, Sri Lanka

Student: Fathima Aroosa

Supervisor: Gamunu Samarakoon Arachchige and Britt M.E. Moldestad

External partner: University of Sri Jayewardenepura, Sri Lanka - A.R. Nihmiya, Udara S.P.R. Arachchige

Shahjalal University of Science and Technology, Bangladesh - Md Salatul Islam Mozumder

Summary:

This study explored the assessment of technologies for small-scale biogas treatment of agricultural waste in Sri Lanka. The study's main objective is to evaluate the current small-scale anaerobic technologies. This evaluation was conducted through an extensive literature review, focusing on developing countries with conditions similar to Sri Lanka. Additionally, by integrating the simulation process using the Anaerobic Digestion Model No. 1 (ADM1), which is widely used to simulate and predict the behavior of the AD process. This model, coupled with AQUASIM 2.0 software, the study endeavored to forecast and analyze the performance of AD. The current evaluation conducted in this study suggests fixed dome, floating drum, and plug-flow bag technologies as particularly suitable for small-scale agricultural waste treatment. According to the simulation performed preliminary, the optimal performance of the AD system with a CSTR-type reactor with a volume of 8 m^3, flow rate of 1.0 m^3/day, and an 8-day hydraulic retention time in simulated conditions resulted in the highest methane percentage.

Preface

This study has been conducted as part of my MPhil studies at the University of Sri Jayewardenepura, Sri Lanka. As part of a six-month exchange Programme, I had the privilege of embarking on a transformative academic journey during my initial research phase at the University of South-Eastern, Norway. The focus of this study is to present an overview of potential technologies for small-scale biogas treatment of agricultural waste in Sri Lanka. Additionally, this work provides a foundational understanding of the process simulation involved in anaerobic digestion model no. 1 (ADM1), facilitated through AQUASIM software.

I express my heartfelt thanks for the scholarship generously provided by the Norwegian Government under the NORPART project, which aims to establish a research-based education system for developing renewable energy technology in a circular economy.

I extend my sincere gratitude and appreciation for the support, guidance, and mentorship provided by my esteemed supervisors. Their knowledge, support, and helpful feedback were crucial in shaping this work.

Porsgrunn, 14.12.2023

Fathima Aroosa

Contents

Nomenclature

AD	Anaerobic Digestion
ADM1	Anaerobic Digestion Model No.1
APFR	Anaerobic Plug Flow Reactor
BGP	Biogas Plant
CBM	Compressed Biomethane
CHP	Combined Heat & Power
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
EU	European Union
HRT	Hydraulic Retention Time
IWA	International Water Association
LBM	Liquified Biomethane
LCFA	Long Chain Fatty Acid
LNG	Liquefied Natural Gas
LPG	Liquified Petroleum Gas
MSW	Municipal Solid waste
OLR	Organic Loading Rate
PSA	Pressure Swing Adsorption
TS	Total Solid
VFA	Volatile Fatty Acid
VS	Volatile Solid
WWTP	Waste Water Treatment Process

List of Tables

List of Figures

1 Introduction

This chapter initiates the study by introducing the context for biogas production, providing a brief introduction of the ADM1 in the background section. Subsequent sections outline the primary objectives of this thesis and present an overview of the forthcoming report.

This chapter initiates the study by introducing the context for biogas production and providing a brief overview of the ADM1 in the background section. Subsequent sections outline the primary objectives of this thesis and present an overview of the forthcoming report.

1.1 Background

The increase in population and accelerated urbanization is increasing reliance on traditional energy sources. This increase intensifies the energy demand and contributes to environmental issues such as climate change. There is a pressing need to shift from conventional energy systems to non-conventional ones to safeguard the environment and ensure the stability of national economies [1].

One highly effective solution in this context involves harnessing energy from biomass sources, particularly biogas [2]. Anaerobic Digestion (AD) is a complex microbial process that breaks down organic materials without oxygen, producing biogas primarily composed of methane (CH_4), carbon dioxide (CO_2), and trace gases. The process unfolds in four stages. In hydrolysis, complex molecules like carbohydrates, fats, and proteins are cleaved into simpler components such as short sugars, fatty acids, and amino acids. During acidogenesis, fermentative bacteria convert sugars into a mix of organic acids, alcohols, CO_2, and hydrogen (H2). In acetogenesis, fermentation byproducts transform into acetic acid, hydrogen, and CO_2. Methanogenesis, the final phase, is executed by strictly anaerobic methanogenic bacteria, producing predominantly CH_4 and CO_2 [3].

Biogas is considered a form of clean energy [4]. It is a versatile energy source and can be directly utilized for heating and electricity, making it a viable option for applications such as internal combustion generators and other power-producing facilities. Moreover, the byproduct of the AD process, known as digestate, serves as an excellent soil additive [5]. As per the energy balance report for the year 2020 by Sri Lanka's sustainable energy authority, the electricity generation distribution by sources is depicted in percentage in Figure 1.1.

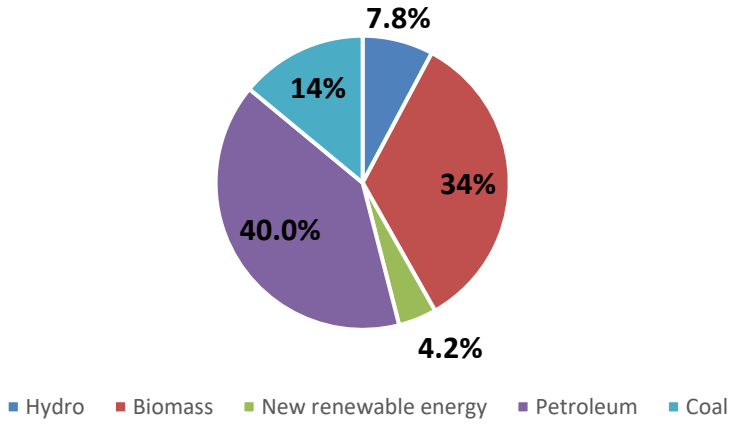

Figure 1.1: Primary energy supply in Sri Lanka in 2022 [6].

During the 22nd session of the United Nations Framework Convention on Climate Change, the Sri Lankan government committed to achieving 100% renewable energy for electricity generation by 2050 [7]. As part of this initiative, the Government aims to develop 10,000 MW of renewable energy capacity within the next decade. To fulfill this target, the Sri Lankan government has outlined plans to integrate 104.62 MW of electricity generated from agricultural, municipal, and industrial sources by 2025 [8].

Figure 1.2 illustrates the suggested energy provision in Sri Lanka by 2030.

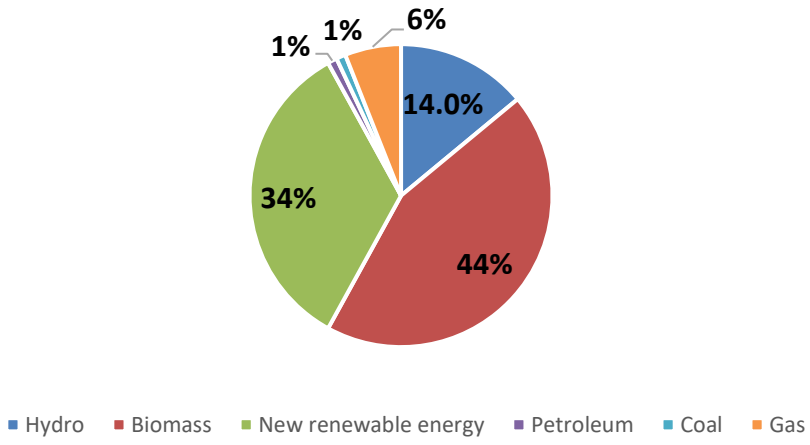

Figure 1.2: Proposed energy supply in Sri Lanka by 2030 [9].

Agriculture employs 33.7% of the population in Sri Lanka, with 41.8% of the land area dedicated to agricultural activities. Additionally, agriculture contributes 7.5% to the Gross Domestic Production as of 2022 [10],[11] Given the significance of agriculture in sustaining livelihoods, establishing biogas plants holds substantial promise to address energy needs, enhance cooking facilities, and effectively manage waste [10].

Mathematical models and simulation processes can forecast reactor behavior across a broader range of designs and operating conditions and in a significantly shorter time than lengthy experimentation [12]. Among the numerous mathematical models available for characterizing AD, ADM1, formulated by the IWA (International Water Association) Task Group, is the most comprehensive. It has attracted increasing attention due to its broad applicability [12]. Motivated by this versatility, the current study utilizes the ADM1 model to simulate the AD of cattle manure through AUASIM 2.0 software.

This study will significantly impact sustainable energy practices. Deriving renewable energy from the AD of agricultural waste stands as a transformative waste-to-energy solution. These findings contribute substantially to sustainable practices. The economic and social impacts, coupled with enhanced localized energy security, underscore the potential of small-scale biogas technologies, providing valuable insights for private industry investors and municipal decision-makers in developing biogas plants.

1.2 Objectives

The primary objective of this study is to assess the potential technologies for the small-scale treatment of agricultural waste to produce biogas in Sri Lanka. The specific objectives to be addressed during this study are as follows:

- Conduct an in-depth literature review focusing on advanced technologies converting agricultural waste into biogas.
- Identify technologies that are well-suited to the specific contextual of Sri Lanka.
- Gather pertinent data required for the ADM1.
- Utilize AQUASIM software to simulate to simulate the collected data.
- Estimate the capacities of the AD process and analyze the simulated results.
- Provide recommendations for future research endeavors.

1.3 Report Outline

Chapter 1 introduces the report by providing a brief overview of the background, objectives, and the study's outline. Chapter 2 provides a thorough examination of the existing literature on biogas production along with a fundamental exploration of the ADM1 model. Chapter 3 outlines the conceptual framework for simulating the AD of cattle manure using AQUASIM software based on the ADM1. The results of the simulation and detailed discussion are provided in Chapters 4 and 5, respectively. The conclusion is included in Chapter 6. For future recommendations, a list of references is provided at the end of the report, followed by appendices.

2 Literature Review

The literature review includes various research and practical applications to gain insights into biogas production, processes, technologies, use, and challenges.

2.1 Biogas Production and Composition

Biogas production is a well-established sustainable method that generates renewable energy and treats organic waste [13]. AD is the crucial process in which microorganisms break down complex organic materials into biogas under anaerobic conditions, which can serve as a versatile fuel source [3].

The biogas plant process comprises five key phases, including the pretreatment of raw materials, AD, purification of biogas, subsequent utilization, and the final treatment of digestate. The pivotal component within the biogas plant is the anaerobic digester, which should be carefully chosen based on specific operational requirements [14].

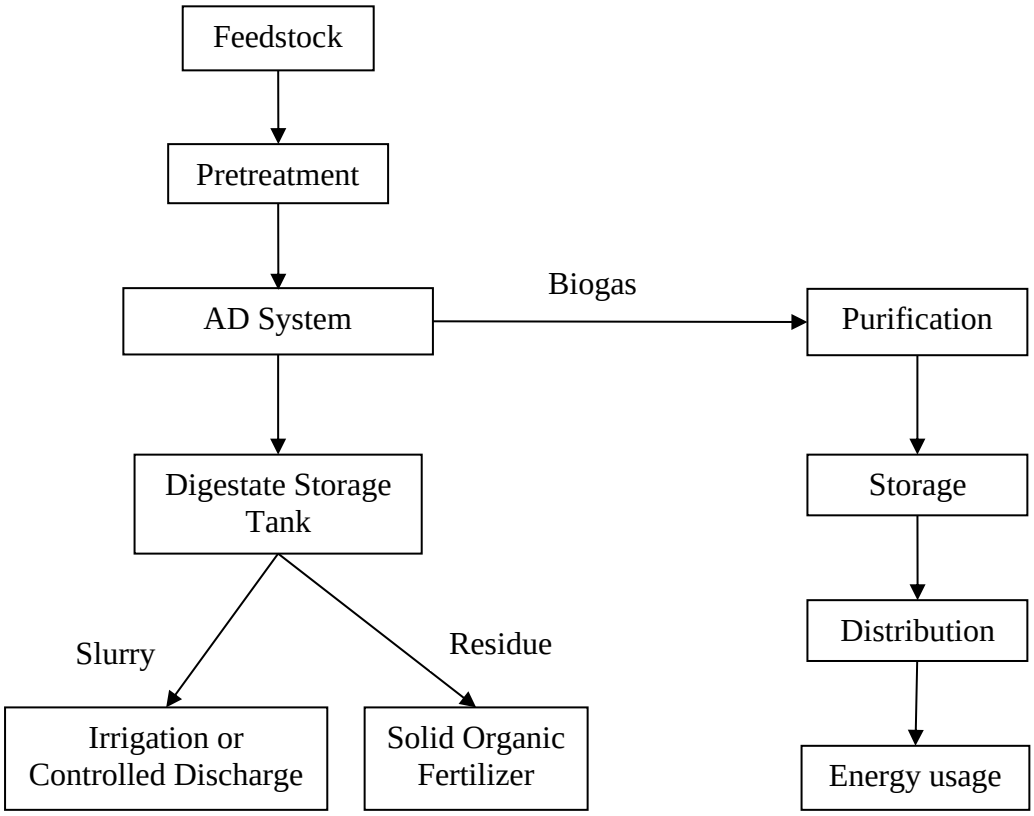

Figure 2.1: The general operational flowchart of a biogas plant [14].

The composition of biogas depends on the feedstock. It mainly consists of CH_4, CO_2, and small quantities of some other gases [1].

Table 2.1 displays the chemical composition of unprocessed biogas.

Table 2.1: Chemical composition of biogas [1].

Parameter	Biogas (vol%)
Methane (CH_4)	40-75
Carbon dioxide (CO_2)	15-60
Hydrogen sulfide (H_2S)	0.005-2
Nitrogen (N_2)	0-2
Oxygen (O_2)	0-1
Carbon monoxide (CO)	<0.6

2.2 Biochemical Mechanism of Biogas Production

The biogas production process comprises four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, with each stage being facilitated by different specialized microorganisms [15].

Figure 2.2 illustrates the stages of the anaerobic process.

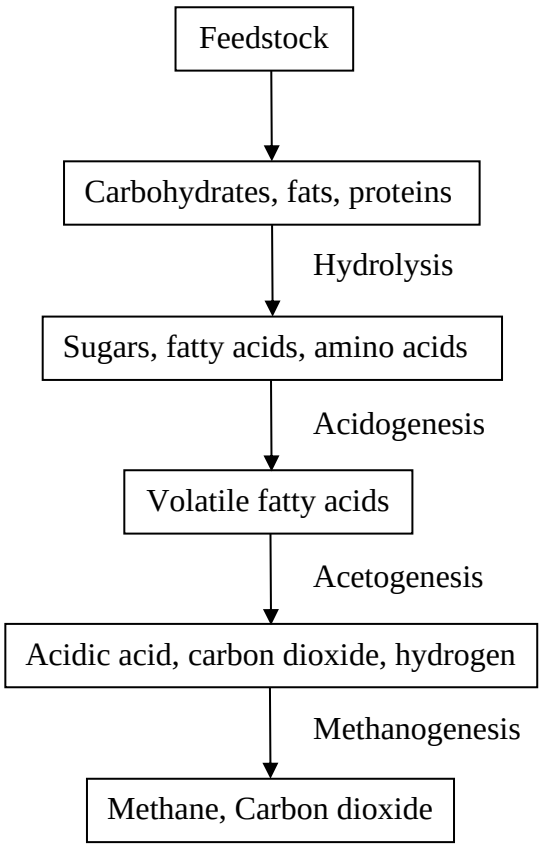

Figure 2.2: Anaerobic digestion process stages [16], [17].

2.2.1 Hydrolysis

Hydrolysis initiates the initial stage of the AD process. Here, fermentative bacteria excrete extracellular enzymes like cellulases, amylases, proteases, and lipases to degrade complex organic compounds such as proteins, carbohydrates, and lipids into easily soluble substances such as simple forms of sugars, amino acids, and fatty acids [18].

During the hydrolysis phase of a biogas production process, various bacterial groups like *Bacteroides, Clostridium,* and *Acetivibrio* play an active role [16]. The organic waste subjected to hydrolysis is a valuable energy source for biogas production, primarily because it primarily consists of lignin, hemicellulose, and cellulose [17].

2.2.2 Acidogenesis

Acidogenesis is the second step, where the simple monomers created during hydrolysis undergo a bioconversion process to generate volatile fatty acids like acetic acid, propionic acid, and butyric acid, along with minor amounts of alcohols, ketones, CO_2, ammonia (NH_3), hydrogen sulfide (H_2S), and H_2 [3]. This stage is called fermentation in AD, where a series of reactions occur. The specific number and nature of these reactions depend on the types of microorganisms in the digestion environment and the substrates available for fermentation [18].

Many of the microbes responsible for hydrolysis also play vital roles in the fermentation process. In addition, various microorganisms, such as *Enterobacterium, Acetobacterium,* and *Eubacterium,* among others, are actively engaged in the fermentation process [16].

2.2.3 Acetogenesis

Acetogenesis is the third step of the AD process. H_2-producing acetogenic bacteria break down and transform propionic acid, butyric acid, and alcohols into acetic acid, H_2, and CO_2. On the other hand, homo acetogenic bacteria convert H_2 and CO_2 into acetic acid [14]. Genera like *Syntrophomonas, Syntrophic*, *Clostridium*, and *Nitrobacter* contain many organisms capable of carrying out acetogenesis [16].

2.2.4 Methanogenesis

In the fourth stage of the AD process, known as methanogenesis, microorganisms with methanogenic capabilities transform H_2, CO_2, and acetic acid into CH_4. This phase is facilitated by various methanogenic microorganisms, including *Methanosarcina spp, Methanothrix spp, Methanobacterium, Methanococcus,* and various other methanogenic species [17].

2.3 Feedstock Used for Biogas

Various feedstocks are suitable for AD, including agricultural waste, municipal solid waste, and sewage sludge. This section presents a brief description of each feedstock suitable for biogas production.

2.3.1 Agricultural waste

Agricultural wastes are the residual materials generated while producing and processing from agriculture, such as fruits, vegetables, meat, poultry, dairy items, and crops. These materials may contain substances that have potential benefits for humans but are considered

economically unviable due to the expenses associated with collecting, transporting, and processing them for valuable purposes [19].

Agricultural waste offers several advantages, including its diverse sources, cost-effectiveness, and renewable. When employed for environmental pollution management, it holds promising prospects for the efficient utilization of resources [20]. Agricultural waste can be categorized into several categories, including crop residues, industrial processing waste, livestock waste, and food waste [21].

- Crop residues

The cultivation of field crops produces significant quantities of organic waste materials, which can be utilized as a valuable resource for the potential generation of biogas. This is particularly significant in the case of straw, as it represents the primary organic byproduct resulting from the cultivation of field crops. Some other residues are leaves, stovers, and seed pods [22].

- Agro-industry waste

This category includes byproducts generated in food processing sectors, such as vegetable and fruit peelings, the remains of fruits after juice extraction, residual starch from starch production facilities, sugarcane bagasse, molasses from sugar manufacturing, deoiled seed cake from edible oil production, as well as materials like chicken skin, eggs, meat, and animal fats stemming from slaughterhouses and meat processing industries [21].

- Livestock waste

Livestock manure is the primary source for generating biogas among various agricultural residues [14]. The primary categories of livestock waste encompass liquid manure, solid manure, wastewater, bedding materials, and disinfectants [21].

Table 2.2 displays a range of agricultural wastes suitable for biogas production in Sri Lanka and their corresponding methane yield data.

Table 2.2: BM potential of various agricultural waste [21].

Agricultural waste	Methane yield (L/kg VS)
Rice straw	302
Sugarcane bagasse	278
Corn stover	338
Orange peel	217
Pig manure	495
Cattle manure	398

2.3.2 Municipal Solid Waste

MSW is composed of household waste, food waste, garden waste, etc. The AD of the organic portion of this municipal waste is an efficient and sustainable method that tackles waste management and bioenergy production simultaneously. Nevertheless, MSW's complexity and diverse nature often pose obstacles to the effectiveness of AD [23].

2.3.3 Sewage Sludge

Typical sewage sludge consists of primary sludge, separated from wastewater during pre-settling, and excess biological sludge from the activated sludge system. The characteristics of sewage sludge may vary slightly among different countries and areas [24].

2.4 Factors Affecting Biogas Production

Biogas production is a complex process influenced by various factors. Understanding and optimizing these factors are essential for enhancing biogas production efficiency and sustainability. The following factors will affect the biogas production.

2.4.1 Feedstock Characters

- Nutrient Content

Certain micronutrients and macronutrients are essential for the sustenance and proliferation of the microorganisms engaged in the AD process. Maintaining a proper nutrient balance is crucial, with macronutrients including carbon, nitrogen, phosphorus, and sulfur being essential. Aiming for a recommended carbon-to-nitrogen ratio between 16-25:1 is advisable [25].

Micronutrients such as iron, cobalt, nickel, zinc, selenium, tungsten, magnesium, chromium, and molybdenum are essential for microorganisms, even though they are needed in deficient concentrations. These micronutrients are the foundational elements for microorganism growth and play roles in co-precipitation, enzymatic functions, and biochemical reactions [26].

- Particle Size

Reducing the particle size of waste creates a more extensive surface area available for the initial binding of exoenzymes. This, in turn, enhances the degradation process and increases biogas production [25]. The appropriate particle sizes for solids in the AD process differ depending on the standards followed. For instance, according to EU Regulation EC 208/2006, the maximum allowable particle size for effective digestion is 12 mm. Smaller particles are necessary to enhance the efficiency and efficacy of the AD process. However, tiny particles can potentially cause blockages in the digestion system [27]

- Toxic or Inhibitory Compounds

Inhibitors are substances that have an adverse or detrimental impact on a system [28]. In the AD process, there are specific compounds that, when their concentration surpasses certain thresholds, can diminish biogas production or, in more severe cases, lead to a critical deterioration of the process. These compounds can be either toxic substances or intermediate products of metabolism [29].

One of the prevalent hindrances in the AD process is the elevation in ammonia concentration. Ammonia is found in various organic residues, like swine or poultry manure, and highly protein-rich sludge. Additionally, ammonia can be generated from protein decomposition or

other substances like urea. It has been documented that a total ammonia nitrogen concentration ranging from 1.7 to 14 g/L can result in a 50% reduction in methane production [29].

Another compound linked to the detrimental impact on the biogas production process is long-chain fatty acids (LCFA). Several agro-industrial residues, such as slaughterhouse waste, food waste, and olive-mill wastewater, contain significant LCFA concentrations. The inhibition caused by LCFA is attributed to the buildup of compounds generated during β-oxidation, which cannot undergo further oxidation due to unfavorable thermodynamic reactions [30].

Another issue faced by biogas plants pertains to foaming occurrences. These incidents can be triggered by operational problems such as inadequate mixing, organic overloading, or specific biosurfactants generated during AD [29].

2.4.2 Process Parameters

- Temperature

The temperature within the digester is a critical factor influencing the AD process as it directly regulates the metabolic activity of the microorganisms responsible for methanogenesis. Any departure from the ideal temperature ranges can lead to reduced microbial activity, consequently lowering the efficiency of the digester [17].

The appropriate temperature for the AD process should be tailored to the specific category of microorganisms that are most active in the digestion process, including psychrophilic, mesophilic, and thermophilic microorganisms. These microorganisms thrive at different temperature ranges, with psychrophiles preferring 10°C, mesophiles thriving between 20-45°C, and thermophiles requiring temperatures exceeding 50°C [27].

- pH

The pH level is crucial in the fermentation process due to its direct impact on the breakdown of substrates. Within bioreactors, methanogenic microorganisms are notably responsive to pH fluctuations. When the pH drops excessively, it can inhibit AD, and conversely, unduly high pH levels can result in the formation of toxic free ammonia, which is harmful to methanogenic microorganisms [25].

- Moisture Content

Moisture is a critical factor for facilitating the metabolic processes and activities of microorganisms involved in AD. Depending on the moisture content, AD can be conducted under two main conditions: submerged (wet) or solid-state (dry). Submerged AD occurs when solid concentrations are below 15%, while solid-state AD is conducted with solid concentrations exceeding 15%. Submerged AD offers advantages such as reduced inoculum needs, shorter retention times, and higher methane production. Conversely, solid-state AD gives benefits such as smaller digester volumes, lower energy requirements for heating and mixing, and easier management of the resulting digestate [25].

- Inoculum

The choice of inoculum source holds significance as it profoundly impacts various aspects of the AD process. These include methane content, degradation efficiency, lag phase, digestion outcomes, enzyme activity, microbial community, as well as parameters such as total solids (TS), volatile solids (VS), pH, and the content of carbon and nitrogen [31].

2.4.3 Operational and Design Parameters

- Hydraulic Retention Time (HRT)

HRT represents the typical duration during which the substrate remains within the reactor. Providing microorganisms with an adequate period to transform organic matter into biogas is crucial. The retention time's term is likely the primary process factor that significantly influences the quantity and speed of methane production [32].

Elevating the retention time results in a more significant reduction of volatile solids, a need for a larger digester capacity, and improved adaptability to pH fluctuations and harmful substances. Conversely, reducing retention times leads to decreased digester size requirements and, consequently, reduced initial expenses while maintaining the same quality and quantity of biogas production [32].

HRT periods range from 10 to 25 days. In colder climates, HRT can extend to as much as 100 days, in contrast to the 30-50 days observed in warmer regions. Employing shorter retention times poses the risk of washing out bacteria, necessitating larger digesters for longer retention durations [27].

- Organic Loading Rate (OLR)

OLR quantifies the daily supply of COD or VS per unit volume of a digester. OLR is a pivotal parameter that significantly influences the AD process's stability, efficiency, and overall cost [33]. Typically, the OLR is kept as low as feasible to provide microorganisms with ample time to break down substrates and boost biogas production. When the loading rate is elevated, there is a greater likelihood of producing unprocessed materials like fatty acids, leading to decreased pH within the environment. This disrupts the balance in the AD process [18].

- Solid Retention Time (SRT)

SRT represents the average time solid particles remain within the digester [25]. Typically, the Hydraulic Retention Time HRT and Solids Retention Time SRT are equivalent in most scenarios. However, in digestion tanks where a portion of the residuals is reintroduced into the process, the SRT exceeds the HRT [27]. This phenomenon is evident in the digestion of industrial wastewater, mainly when the inflow contains a higher proportion of water content for that recirculating digested, concentrated biomass sludge enables extended retention periods to decompose incoming organic material [18].

- Mixing

The mixing procedure facilitates the interaction between microorganisms, substrates, and essential nutrients while ensuring an even temperature distribution within the substrate. Gentle mixing additionally encourages the creation of aggregates and prevents the removal of methane-producing organisms from the substrate due to liquid washout. Conversely, mixing helps decrease sedimentation and mitigates the risk of foaming [18].

On the other hand, mixing the dry solids mechanically is a challenging and expensive task. Furthermore, utilizing biogas recirculation for mixing can result in the loss of biogas. Nevertheless, biogas recirculation is used for low-solids processes, while mechanical mixing is employed for high-solids processes [25].

2.5 Anaerobic Digestion Technologies

AD technologies have been adopted in various countries on both small and large scales. These technologies can be tailored to suit the volume and characteristics of the feedstock. A typical schematic diagram of a small-scale biogas system is shown in Figure 2.3.

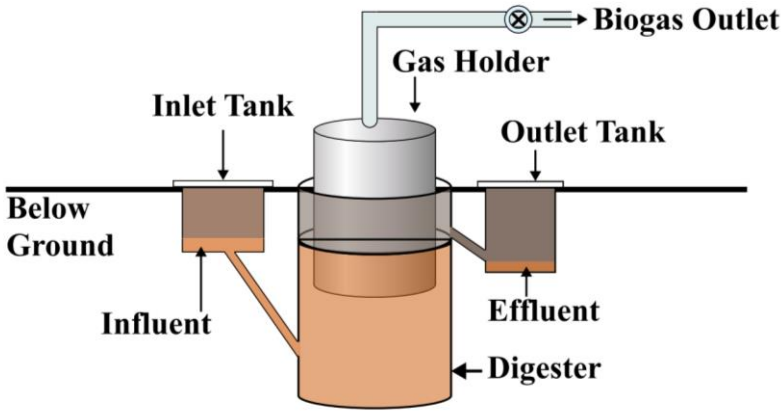

Figure 2.3: Simple schematic diagram of biogas plant [34].

2.5.1 Types of Digesters

The core component of a biogas facility is the digester, where the AD process takes place, converting organic material into biogas. The choice of reactor is pivotal in ensuring the digester unit's effectiveness, as it directly impacts the overall process efficiency and biogas production. [18]. Figure 2.6 illustrates the categorization of digesters based on various criteria.

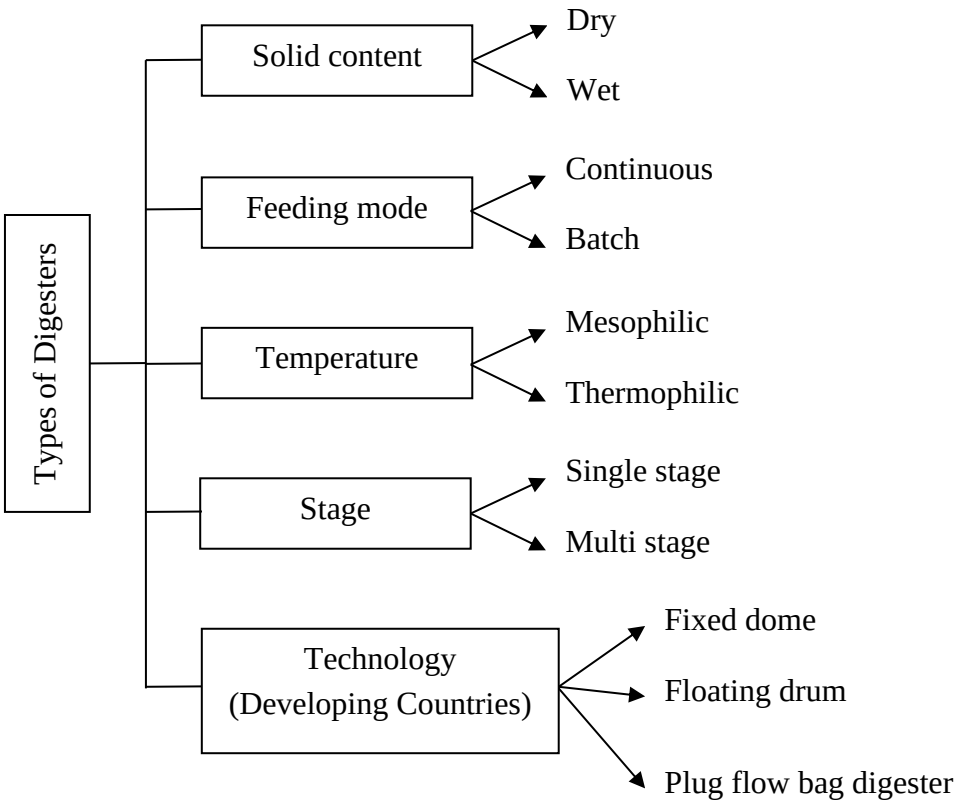

Figure 2.4: Types of digesters [35], [36].

The small-scale biogas technologies that are prevalent in developing countries, such as fixed dome, floating drum, and plug flow bag digesters, have been recognized. Descriptions of these digesters are provided below.

- Fixed dome digester

The fixed dome digester comprises an immobile gas holder positioned on top of it. As gas production initiates, the slurry is displaced into the compensation tank. The elevation disparity between the slurry level in the digester and that in the compensation tank, along with the volume of stored gas, contributes to the rise in gas pressure [37]. It was developed in China and also implemented in India, Nepal, Sri Lanka, Uganda, and Tanzania [38].

Figure 2.5 depicts the schematic diagram of the fixed dome digester.

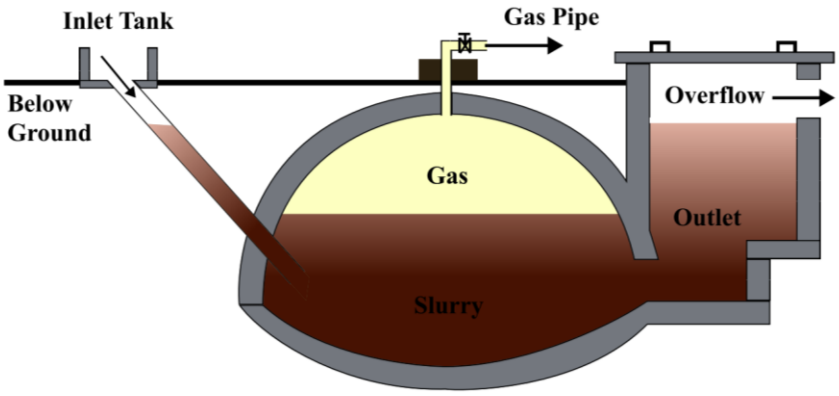

Figure 2.5: Schematic diagram of fixed dome digester [39].

- Floating drum digesters

Floating drum digesters share similarities with fixed dome digesters but feature a distinctive floating gas bell mechanism for biogas collection. The design of the digester consists of a concrete mixing tank that contains two chambers divided by a partition wall and interconnected at the digester's upper section. It also incorporates a stainless-steel cylindrical drum or gas holder and an outlet tank responsible for removing the slurry from the system [40]. Implemented primarily in India [38].

Figure 2.6 illustrates the visual representation showcasing the layout and structure of a floating drum digester.

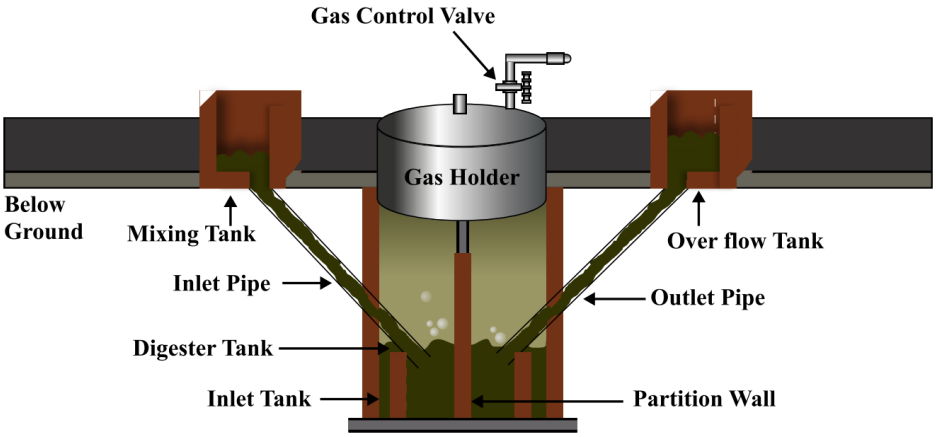

Figure 2.6: Schematic diagram of floating drum digester [41].

- Plug-flow bag digesters

This technology is also referred to as the plastic tubular digester. Typically, polyethylene is the primary material used in constructing tubular digesters, although PVC (specifically, geo-membrane PVC) is starting to gain usage. PVC digesters are pricier than polyethylene digesters but offer a longer lifespan due to their durability. The digester is a tubular bag facilitating slurry flow from the inlet to the outlet. In the upper section of the digester, biogas is collected through a gas pipe connected to a reservoir [40]. Implemented in South America, South Asia, and Africa [38].

Figure 2.7 represents the visual depicting the design of a plug flow digester.

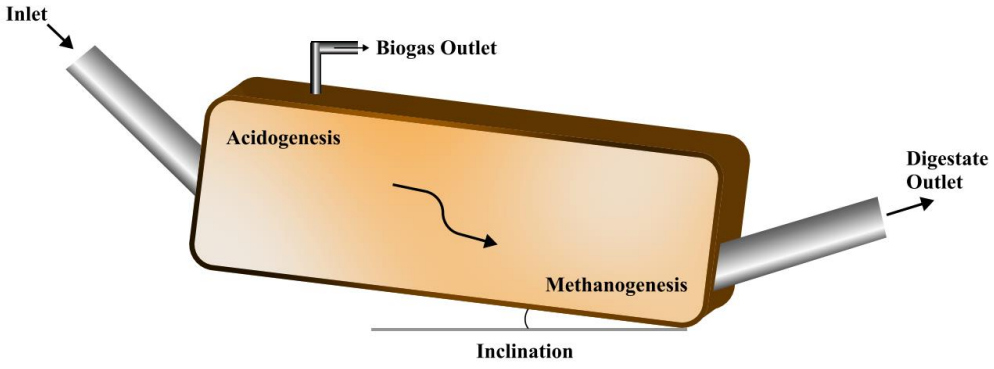

Figure 2.7: Schematic diagram of a plug flow digester [42].

2.5.2 Reactor Technologies Used in AD

Various reactors are employed for biogas production, each designed for specific purposes. Some of the reactor types are outlined below.

- Anaerobic plug-flow reactor (APRF)

Anaerobic Plug-Flow Reactors (APFRs) are elongated rectangular channels characterized by inflow at one end and outflow at the other, with mixing rarely occurring. Typically, these tanks or pipelines are situated above ground. Specific processes within APFRs can exhibit both thermophilic and mesophilic conditions. These high-rate digesters find commercial applications in treating diverse organic wastes, including animal manure slurries, distillery effluent, and the organic components of municipal solid waste [43].

- Biofilm Reactor

In the anaerobic biofilm reactor, the biocatalyst encompasses diverse bacterial species that decompose intricate organic compounds into the ultimate byproducts of methane and carbon dioxide. The biocatalyst in an anaerobic biofilm reactor comprises all the various bacterial species contributing to the degradation of complex organic molecules, producing methane and carbon dioxide as the end products [43].

- Continuous Flow Stirred Tank Reactor (CSTR)

CSTR is characterized by a well-mixed tank where the substrate undergoes continuous addition and withdrawal. The stirring process upholds uniform conditions [41],[44]. CSTRs are one of the most widely utilized reactor technologies for handling municipal food waste. These digesters operate with a continuous feeding system, with equal hydraulic and sludge retention times. Due to the constant mixing and feed flow in CSTRs, not all substrate units experience the same retention time. Some substrate portions are not retained in the reactor, while others are held for an extended duration [45].

- Anaerobic Contact Reactor (ACR)

It is a thoroughly mixed, mechanically stirred tank that incorporates sludge recycling. In this system, the effluent discharged from the tank is directed into a solid-liquid separator, such as a gravity sedimentation tank, a sludge flotation device, or a lamella clarifier. In this separator, solids are reclaimed and reintroduced into the anaerobic digester [43].

- Up-flow Anaerobic Sludge Blanket (UASB)

This reactor typically exhibits a tubular shape. Within this reactor, a sludge bed, consisting of a layer of biomass with high-settling velocity granules, develops at the bottom. This sludge bed serves as the primary site for essential biochemical reactions. Above the sludge bed, a blanket form comprising finely suspended flocs with lower settling velocity. This suspension arises from biogas production in the reactor, stemming from the degradation of soluble organic compounds [44].

2.6 Pretreatment

Pretreatment is one of the essential techniques for processing lignocellulosic biomass in biofuel production. The lignocellulosic biomass consists of three primary structural constituents: cellulose, hemicellulose, and lignin, which remain in a compact matrix form, hindering the accessibility of microbes/enzymes for degradation and hydrolysis [21].

Table 2.3 illustrates the various pretreatment methods alongside the compatible substrates for each technique.

Table 2.3: Pretreatment methods and operation [46], [47], [21].

Pretreatment method	Operation	Suitable substrate
Mechanical	Mechanical pretreatment through size reduction enhances substrate solids by breaking cell walls and rendering biodegradable components more accessible to microorganisms, thereby increasing the speed and efficiency of hydrolysis.	primarily municipal solid waste
Thermal	Thermal pretreatment primarily leads to cell membrane disintegration, resulting in the solubilization of compounds.	Sludge from wastewater treatment
Ultrasound	Ultrasound pretreatment, generated through a vibrating probe, mechanically disrupts the cell structure. The primary effect of ultrasonic pretreatment is the reduction in particle size.	Sludge from wastewater treatment
Chemical	Chemical pretreatment utilizes strong acids, alkalis, or oxidants to decompose organic compounds to break down these substances. Typically, chemical treatment enhances the digestibility of the material.	Agricultural residues
Biological	Biological pretreatment involves the assistance of microbes in delignification and the decomposition of hemicellulose, ultimately enhancing hydrolysis yield.	Agricultural residues Household waste

In cases where individual pretreatment methods fail to yield efficient results, a combined pretreatment approach may be recommended [47].

2.7 Biogas Cleaning

The choice of biogas cleaning methods depends on its intended use or the upgrading process. Various techniques are employed to purify biogas, with specific impurities commonly encountered.

These impurities and their respective removal methods are detailed in Table 2.4.

Table 2.4: Cleaning techniques for common impurities in biogas [3], [18], [48].

Impurities	Impact	Cleaning Techniques
CO_2	Elevated levels of these gases reduce the energy concentration of biogas. Enhance its resistance to knocking in combustion engines.	Absorption in water Chemical absorption using amines Adsorption Membrane separation
H_2O	When reacting with other biogas compounds, water vapor can form corrosive acids such as H2SO4 and HCL. It can be accumulated in the gas pipelines and cause a lower energy content of biogas.	Adsorption using silica or activated carbon Condensation is commonly used.
H_2S	Biogas containing H_2S can cause corrosion in metal components and, when combusted, can release sulfur dioxide. It is highly toxic and poses significant health risks.	Chemical oxidation Scrubbing Adsorption on metal oxides Membrane separation Biological methods
O_2 and N_2	Excess oxygen in biogas is corrosive, and if it surpasses a certain threshold, it can lead to an explosion. Nitrogen in raw biogas may indicate de-nitrification or air leakage within digesters.	Adsorption Desulphurization
Ammonia	Ammonia is highly corrosive, and when burned, it can produce NOx, which contributes significantly to the greenhouse gas effect.	Dissolved in water Organic physical scrubbing
Volatile organic compounds	Volatile organic compounds often have unpleasant odors, are corrosive, and some can even be toxic.	Adsorption using activated carbon.

2.8 Biogas Upgrade

During the biogas upgrading, CO_2 is separated from methane, increasing methane concentration within the treated biogas mixture. This methane content boost enhances the gas's volumetric energy content [18]. Various technologies are employed for biogas upgrading, which are listed below.

- Pressure Swing Adsorption (PSA)

In the PSA method, gas separation is achieved by employing an adsorptive medium. In this process, a gas mixture, known as adsorbates, permeates through the surface of solid materials or adsorbents, while undesirable contaminants are captured due to their molecular size. Adsorbents like zeolites, activated carbon, and carbon molecular sieves are commonly used in this process [49].

- Water Scrubbing

Water scrubbing is a technique employed to separate biogas by taking advantage of the differing solubility of CH_4 and CO_2 in water. CO_2 has a higher solubility in water compared to CH_4. As a result, a water scrubber can remove CO_2 from biogas [48]. To enhance the absorption rate in this process, it is beneficial to reduce the temperature and raise the pressure of the gas mixture entering the absorption tower. This method removes CO_2, H_2S, and NH_3 from the gas mixture. However, water and other particulate matter must be removed before the gas enters this process [18].

- Physical Absorption Using Organic Solvent

This method employs an organic reagent as an absorption agent. The operating principle is akin to that of the water-scrubbing process. However, the organic reagent exhibits superior absorption rates for CO_2, resulting in decreased circulation rates for the absorption liquid. Typically, polyglycerol dimethyl ethers are utilized as organic reagents [18].

- Chemical Absorption Using Organic Solvent

Chemical absorption of biogas using an organic solvent, commonly known as amine scrubbing. It is a technique for separating CO_2 and CH_4 by employing an amine solution [48]. Alkanolamine solutions, including monoethanolamine, diethanolamine, and methyl diethanolamine, are commonly used in biogas upgrading processes. The specific usage and the mixture ratios of these chemicals with water typically depend on the specifications and recommendations provided by the plant manufacturer [18].

- High-pressure Membrane Separation

Membranes are specialized permeable barriers designed to be selective toward specific molecules. The driving forces for the separation process depend on factors like relative concentration, pressure, temperature, and the electric charges of the molecules involved. In the market, three primary types of membranes are commonly employed: polymeric, inorganic, and mixed matrix membranes. Inorganic membranes offer several advantages over polymeric ones, primarily owing to their superior mechanical strength, chemical resistance, and thermal stability [50].

- Cryogenic Separation

Cryogenic separation is a widely recognized technology for gas separation, commonly applied in various large-scale industrial processes. The fundamental principle behind cryogenic techniques is that gases like CO_2 and H_2S liquefy at distinct pressure and temperature levels. Cryogenic plants function at extremely low temperatures (around -170ºC) and high pressures (approximately 80 bar). Cryogenic technology is effective for purifying biogas and minimizing CH_4 losses. However, the current challenges associated with scaling down the process have increased specific costs, making it less economically viable for smaller applications [51].

2.9 Biogas Storage

Once CO_2, H_2S, and water vapor are removed from biogas, Biomethane (BM) is the resulting product. Selecting a suitable storage system for BM is crucial in determining the future performance of integrated energy systems [52]. The biogas storage methods are described below.

- Gas Grid Storage

The significance of purifying biogas has increased in recent years, attributed to the depletion of natural gas resources and diminished quality. It is crucial to upgrade biogas efficiently and use suitable methods to match natural gas quality. This is especially important for injecting biogas into the current natural gas grids [53]. An essential consideration is that this storage method for BM may not be practical in Sri Lanka due to the absence of a suitable gas grid infrastructure [18].

- Below Ground Reservoir

BM has the advantage of being storable in the extensive natural gas storage facilities. This surpasses the storage capacities of electricity, compressed air, or water storage methods. The underground reservoir storage options comprise depleted gas and oil reservoirs, salt caverns, and aquifers [49][52].

- Compressed Tank

In this process, BM producers fill their products into sizeable pressurized gas containers and then distribute them to centralized gas filling stations or industrial consumers using a transportation medium. One benefit of this approach is that it saves significant space. However, it is essential to implement substantial safety measures for these tanks, such as installing fixed pressure relief valves and rupture disks [52].

- Liquefaction

The liquefaction process involves cooling the biomethane gas to -162°C at 1 atmosphere pressure, transforming it into a liquid form called liquefied biomethane (LBM). LBM is an optimal solution for harnessing biomethane resources in remote locations where a pipeline network is unavailable. Nevertheless, it is essential to note that LBM requires more energy than liquefied natural gas [54].

- Bottling

Bottling biogas is proposed as a viable option to deliver renewable and clean energy to individual households. This involves producing biogas at larger-scale facilities and then distributing cylinders or other storage containers filled with biogas to homes, similar to the delivery methods used for Liquefied Petroleum Gas (LPG) or Compressed Natural Gas (CNG) [55].

- Adsorbed Storage

Adsorbed BM (ABM) is an emerging storage technology where BM is absorbed by a porous adsorbent material at relatively low pressures, typically up to 45 bar. Some adsorbents can achieve remarkable storage capacities even at atmospheric pressure. When a BM storage container is filled with an appropriate adsorbent material, it can hold more BM than the same container without the adsorbent, filled to the same pressure. Compared to Compressed BM (CBM), ABM can store approximately five times more BM per unit storage volume at 30 bars and ten times more at 10 bars [52].

2.10 Biogas Usage

Biogas is recognized as a conventional and sustainable energy source. The various applications of biogas are described below.

- Electricity Generation

Because upgraded BM possesses a substantial energy density, it can be employed for electricity generation through gas engines, combined heat and power systems, or internal combustion engines paired with generators. The electricity generated can be integrated into the power grid or utilized by industries engaged in electricity production [52], [56].

- Heat Generation

Biogas is suitable for direct combustion in boilers, primarily for heat generation. Modifying natural gas boilers to make them compatible with biogas is also viable. Since farm biomass is pivotal in biogas production, the heat generated can serve various functions. This includes heating digesters, farm structures like pig housing units and sites, and greenhouses, as well as supporting aquafarming and facilitating the cooling or refrigeration of farm products. Additionally, the drying process within agricultural enterprises, such as digestate, wood chips, grains, herbs, and spices, represents a noteworthy and valuable addition to the farm economy [56].

Certain Asian countries, notably India and Pakistan, extensively utilize small bottled cylinders of BM as a cooking fuel in domestic and commercial settings. Additionally, there exists significant potential for employing portable bottled BM for heating purposes among small-scale consumers. Bottling could serve as a supplement to address peak heating demands, particularly in applications heavily reliant on fossil fuels [18].

- Transportation Fuel

Biomethane, obtained by converting biogas through upgrading and cleaning processes, can be an alternative to fossil natural gas for powering vehicles. Utilizing BM as a transportation fuel significantly reduces greenhouse gas emissions, making it a favorable renewable fuel option. From both environmental and economic perspectives, biomethane is a suitable substitute for fossil-based fuels [57].

- Fertilizer

The residual digestate from the digester is abundant in nitrogen, phosphorus, and potassium, making it an excellent fertilizer. As a result of the AD process, plants can readily absorb these nutrient concentrations. The treated effluent serves as a direct and beneficial fertilizer for agricultural purposes. When exported, digestate holds considerable commercial value. The dried effluent can also be used as an adsorbent for extracting lead from industrial wastewater. The biogas slurry proves beneficial for cultivating algae, water hyacinth, and duckweed and supporting poly-aquaculture with fish [42].

2.11 Benefits of Biogas Usage

Utilizing biogas as an alternative and sustainable energy source brings many benefits beyond energy production. It offers many benefits for the environment, the economy, and society.

Table 2.5 summarizes the benefits of biogas production and usage.

Table 2.5: Benefits of biogas production and usage [3], [57], [58].

Sector	Benefits
Environmental benefits	Reduce air and water pollution. Reduce greenhouse gas emissions. Pathogen reduction. Odor reduction. Reduce deforestation. Reduce carbon footprint. Promote resource efficiency. Recovery of nutrients through the utilization of digestate.
Economic benefits	Create employment. Adding value to products. Promote circular economy. Reduce the cost of energy. Reduce environmental costs.
Social benefits	Reduce poverty. Reduce diseases. Waste management. Empower farmer. Improve sanitation and living conditions through waste management.

2.12 Challenges in Biogas Production in Sri Lanka

Biogas technology was initially introduced to Sri Lanka in the 1970s, primarily for research purposes. By 2011, an estimated 5,000 biogas plants were operating, but only one-third were functioning effectively. The Sri Lanka Domestic Biogas Programme significantly expanded this technology, adding 3,150 biogas plants between 2011 and 2014 [59]. Approximately 7,000 biogas plants are believed to be currently present throughout the country, as indicated by [60]. However, precise figures regarding the exact count of biogas plants in Sri Lanka and details about the distribution of various biogas plant models remain undisclosed [59].

Table 2.6 shows the types of biogas plants in Sri Lanka based on their size.

Table 2.6: biogas plant categorization based on their size in Sri Lanka [61].

Description	Size of BGPs (m^3)
Small-scale biogas plants	Less than 12
Medium-scale biogas plants	12-16
Community-scale biogas plants	More than 60

The prevalent types in Sri Lanka include BGPs utilizing the Chinese fixed dome model, the SiriLak Dahara model, and the Arpico model based on floating drum designs, with respective percentages of 72.5%, 21.57%, and 5.88% [61]. The success of biogas production in Sri Lanka is hindered by various challenges, as highlighted in sources [60], [9]:

- Inadequate construction skills or a shortage of technically skilled masons.
- Insufficient feedstock for the digester and improper handling of organic waste.
- Owners lack the necessary knowledge to operate the bio-digester.
- Social acceptance issues related to biogas technologies.
- Insufficient progress in enhancing local capability, conducting research, and developing technologies.
- Significant investment is needed for infrastructure development.

3 Conceptual Modeling

This section provides an overview of the ADM1 modeling and simulation procedure.

3.1 ADM1 Model

The ADM1, created by the Task Group for Mathematical Modeling of AD Processes under the International Water Association (IWA), is an all-encompassing model that offers a detailed account of the vital biochemical reactions and physico-chemical phenomena occurring during AD and encompasses stages such as disintegration and hydrolysis, acidogenesis, acetogenesis, and methanogenesis within the AD process [62].
Figure 3.1 shows the implemented AD model, including biochemical processes.

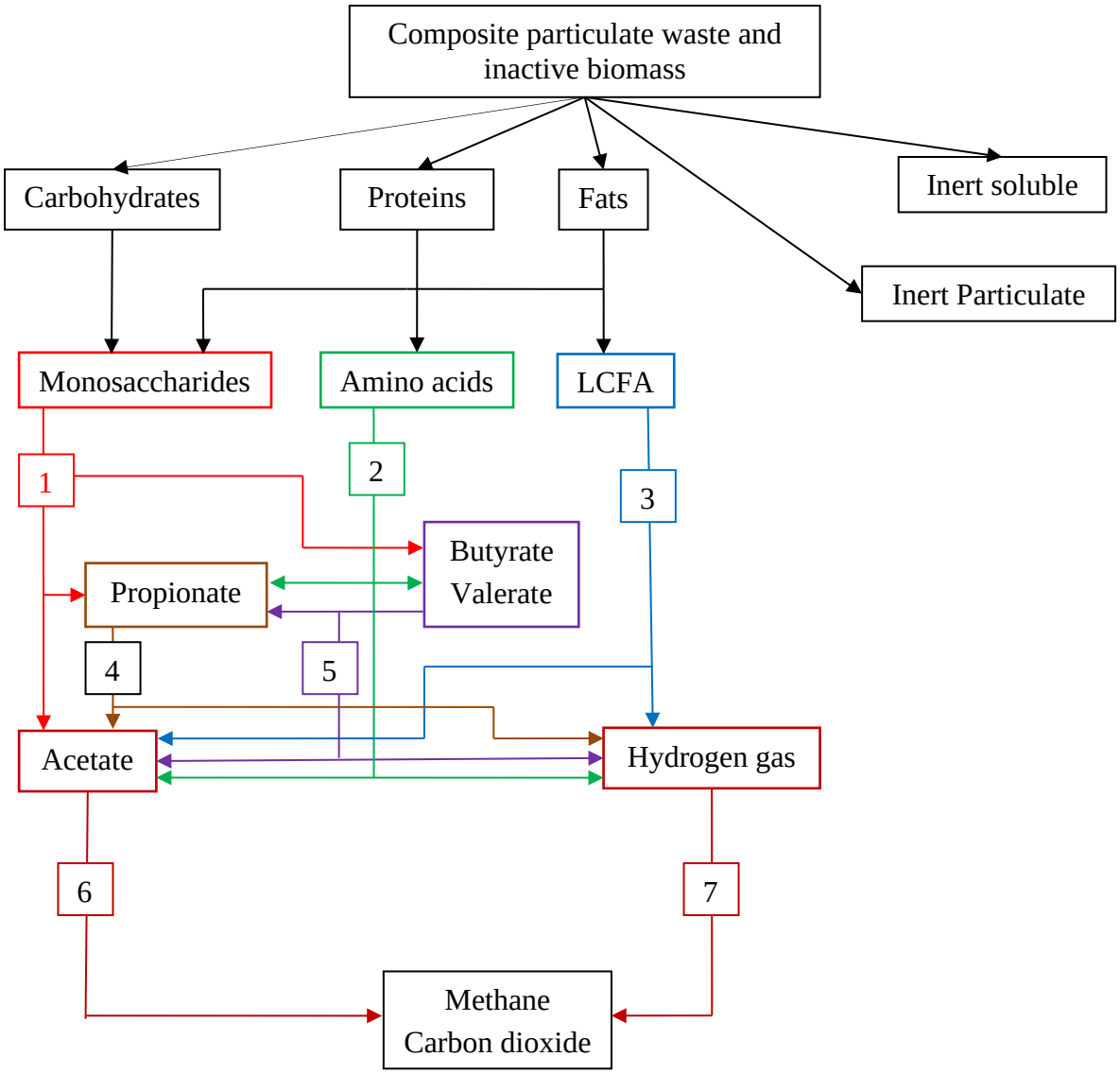

Figure 3.1: The implemented anaerobic model in ADM1 [63].

(1) acidogenesis from sugars, (2) acidogenesis from amino acids, (3) acetogenesis from LCFA, (4) acetogenesis from propionate, (5) acetogenesis from butyrate and valerate, (6) acetoclastic methanogenesis, and (7) hydrogenotrophic methanogenesis

The ADM1 features a fundamental structure depicted in Figure 3.2, where q_{in} represents the incoming flow, q_{out} is the effluent or output flow, and q_{gas} denotes the biogas flow. This model is organized into liquid and gaseous phases, interconnected through mass transfer rates between the two. The liquid phase consolidates the concentrations of physico-chemical components in both the input flow and within the biodigester, while the gaseous phase encompasses the gases generated by AD from the biomass within the biodigester. Biochemical and physicochemical reactions take place in these phases [63].

Figure 3.2 shows the schematic diagram of a single-tank CSTR reactor.

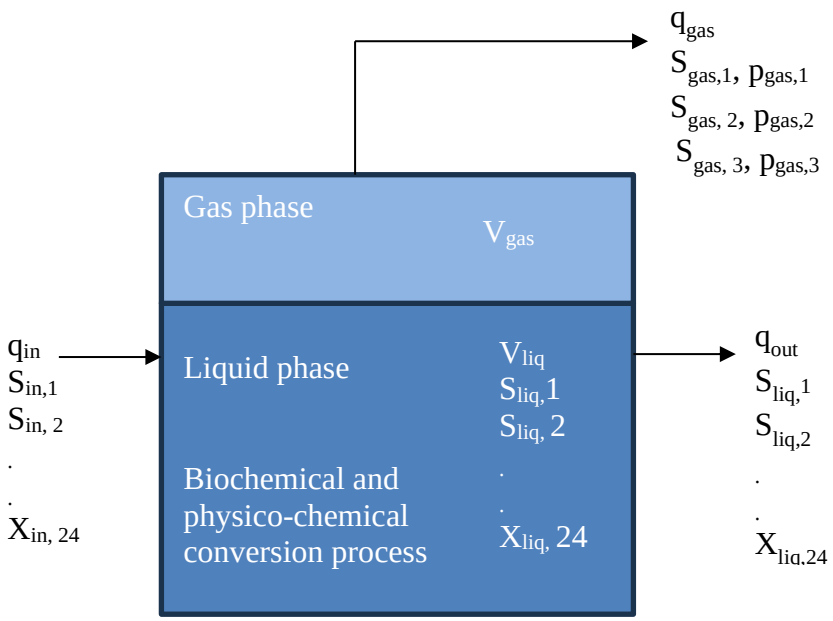

Figure 3.2: Schematic diagram of a typical single-tank CSTR reactor [63].

q - flow, V – Volume, $S_{stream,\ i}$ – concentration of soluble components, $X_{stream,\ i}$ – concentration of particulate components, i – component index (see Appendix B and C)

The ADM1 model comprises 29 dynamic state variables, encompassing 26 variables within the liquid phase. Among these, 14 are soluble, and 12 are particulate. Additionally, the model includes three variables in the gas phase within a continuous stirred-tank reactor (CSTR) system [64].

The characteristics of the input substrate are categorized into soluble components (S), particulate components (X), and operational parameters, forming the input vector of the ADM1. These variables interact with 19 biochemical processes through kinetic rates, stoichiometric ratios, and physical parameters, all of which are integrated into the comprehensive model [65] (see Appendix A, B and C).

3.2 Data Compilation

The dataset, including the necessary state variables for AD modeling of the ADM1 for cattle manure, was obtained from an open-access publication [66]. The dataset provided contains essential parameters necessary for simulating the AD process, as outlined by the ADM1 model.

Tables 3.1 and 3.2 display the specific input ADM1 state variables determined for the AD modeling of cattle manure.

Table 3.1: Set of ADM1 model soluble input state variables

State variable	Unit	Value
S_{su}	$kgO_2 \cdot m^{-3}$	2.95
S_{aa}	$kgO_2 \cdot m^{-3}$	0.15
S_{fa}	$kgO_2 \cdot m^{-3}$	0.17
S_{va}	$kgO_2 \cdot m^{-3}$	0.00
S_{bu}	$kgO_2 \cdot m^{-3}$	0.00
S_{pro}	$kgO_2 \cdot m^{-3}$	0.00
S_{ac}	$kgO_2 \cdot m^{-3}$	0.00
S_{h2}	$kgO_2 \cdot m^{-3}$	0.00
S_{ch4}	$kgO_2 \cdot m^{-3}$	0.00
S_{IC}	$kM\ C \cdot m^{-3}$	0.10
S_{IN}	$kM\ N \cdot m^{-3}$	0.05
S_I	$kgO_2 \cdot m^{-3}$	0.00
S_{cat}	$kmole \cdot m^{-3}$	0.10
S_{an}	$kmole \cdot m^{-3}$	0.02

Table 3.2: Set of ADM1 model particulate input state variables

State particulate variable	Unit	Value
X_c	$kgO_2 \cdot m^{-3}$	0.00
X_{ch}	$kgO_2 \cdot m^{-3}$	84.2
X_{pr}	$kgO_2 \cdot m^{-3}$	4.30

X_{li}	$kgO_2 \cdot m^{-3}$	4.90
X_{su}	$kgO_2 \cdot m^{-3}$	0.00
X_{aa}	$kgO_2 \cdot m^{-3}$	0.00
X_{fa}	$kgO_2 \cdot m^{-3}$	0.00
X_{c4}	$kgO_2 \cdot m^{-3}$	0.00
X_{pro}	$kgO_2 \cdot m^{-3}$	0.00
X_{ac}	$kgO_2 \cdot m^{-3}$	0.00
X_{h2}	$kgO_2 \cdot m^{-3}$	0.00
X_I	$kgO_2 \cdot m^{-3}$	0.29

The kinetic equations, stoichiometry, pH equilibrium, and other equilibrium conditions parameters of this model follow the suggested guidelines specified for mesophilic solid conditions in the ADM1 framework. However, only the hydrolysis coefficient parameter was chosen from the mentioned open-access publication, where a value of 0.08 d^{-1} is determined for carbohydrates, proteins, and lipids.

The selection of reactor volume for the base case for this study was chosen based on the literature review. The most common size for small-scale BGP is 8 m^3 [61]. Furthermore, the reactor conditions are set to be mesophilic, maintaining a temperature of 35 ºC.

Equation 2.1 was used to determine the selected flow rate for this study, resulting in 0.4 m^3/day. The calculation is based on a set value for a reactor volume of 8 m^3 and HRT 20 days.

Digester volume(m^3) = HRT (day)×substate input flowrate(m^3/day) (2.1)

3.3 AQUASIM simulation

ADM1 model built on AQASIM 2.0 software, with parameters customized for a CSTR configuration, was used for the simulation [62].

In the AQUASIM simulation process, the parameters required for the ADM1 model were carefully input. These parameters include essential input state variables and reactor conditions, as detailed in the data collection chapter. Subsequently, the loading conditions for the reactor were defined, specifying influent flow rates and concentrations. The simulation was initialized by putting these parameters into the AQUASIM software, and the model was simulated over a specified time frame of 70-day intervals. Then, the flow rate was increased stepwise to observe how the system responds to dynamic changes. The specific cases are outlined below in Table 3.3.

Table 3.3: Cases with adjusted flow rate

Flow rate (m^3/day)	HRT (days)
0.4	20
0.6	13.3
0.8	10
1.0	8
1.2	7
1.4	6.7
1.6	5
1.8	4.4
2.0	4
2.2	3.6

The AD of cattle manure was simulated using input state variables adopted from another data set from a different publication referenced as [22] for the base case. Mainly, gas flow and adjusted gas pressure were obtained from the results, which are essential from the simulation results.

4 Results

This chapter includes the simulated results of the AD of cattle manure utilizing the ADM1 model and simulated through AQUASIM software.

4.1 Simulation of AD Process

The results of the AQUASIM simulation, which used the ADM1 model with CSTR reactor configuration with a reactor volume of 8 m^3 and flow rate of 0.4 m^3/day, were simulated over 70 days.

4.1.1 Gas Flow

Figure 4.1 illustrates the simulation results of the continued biogas production in the reactor.

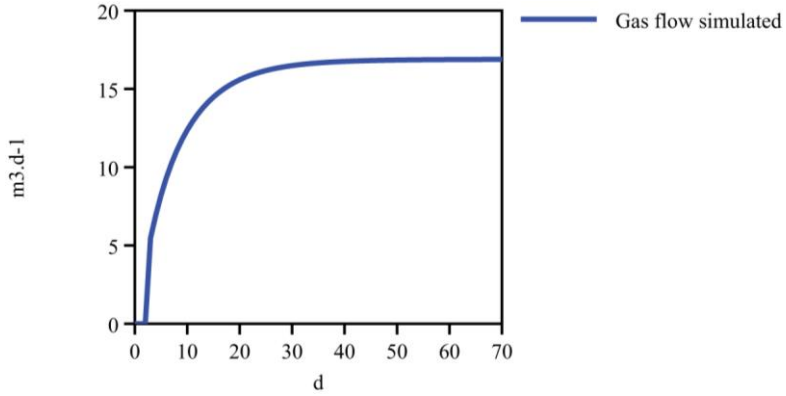

Figure 4.1: Gas flow profile.

4.1.2 Adjusted Reactor Gas Pressure

Figure 4.2 depicts the simulation outcome for adjusted gas pressure in the reactor.

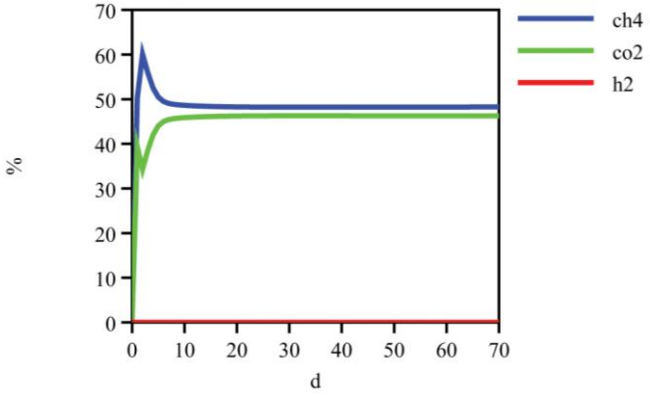

Figure 4.2: Adjusted gas pressure.

4.1.3 pH

Figure 4.3 shows the simulation result of pH change during the period in the reactor.

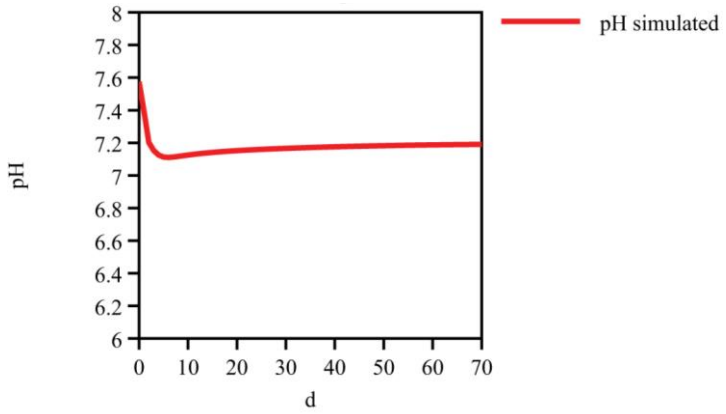

Figure 4.3: pH trend.

4.1.4 Volatile Fatty Acids

Figure 4.4 illustrates the simulation outcome of VFA in the reactor.

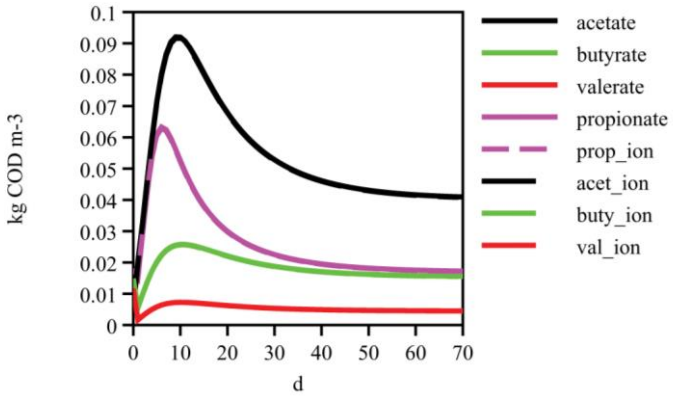

Figure 4.4: VFA concentration.

4.1.5 Biomass

Figure 4.5 shows the simulation results of biomass concentration in the reactor.

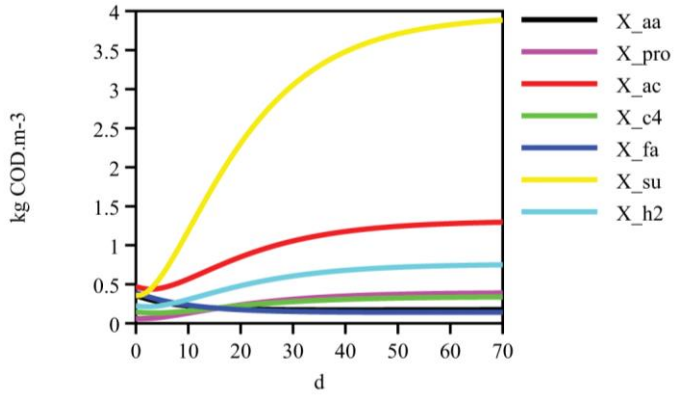

Figure 4.5: Biomass concentration.

4.1.6 Inhibition

Figure 4.6 shows the inhibitory effect inside the reactor.

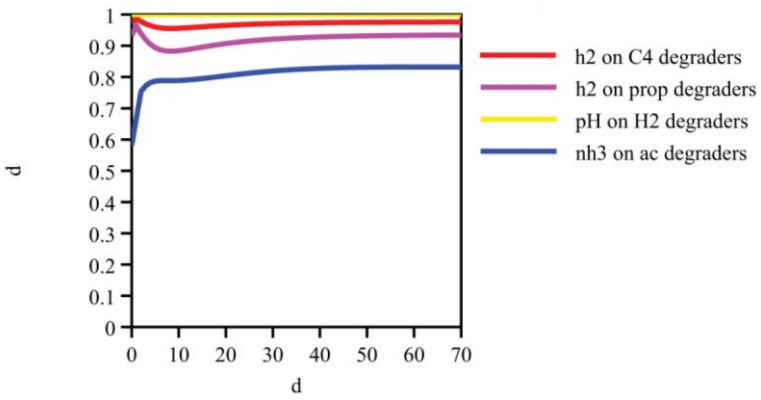

Figure 4.6: Inhibition profile.

4.1.7 Additional Dataset

Figure 4.6 and 4.7 shows the simulated results of gas flow and adjusted gas pressure respectively, from the additional data set.

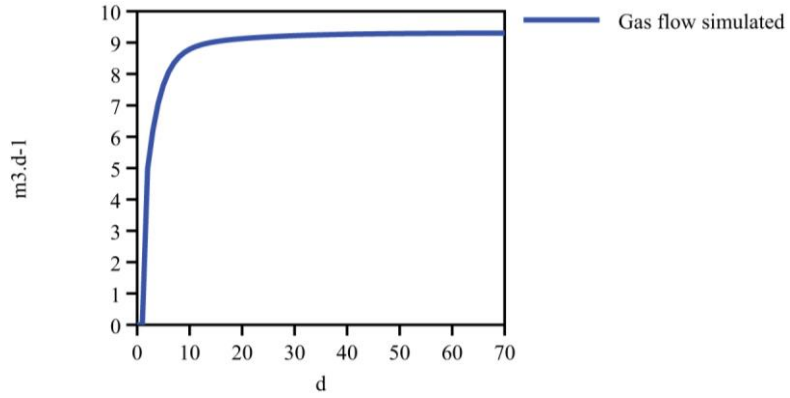

Figure 4.7: Gas flow profile (Additional Dataset).

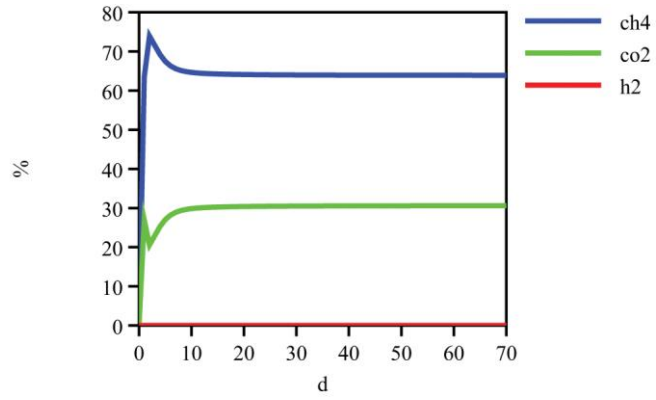

Figure 4.8: Adjusted gas pressure (Additional Dataset).

4.1.8 Variation in Flow Rate

Table 4.1 shows the simulated results for variation in flow rate, together with the calculated HRT values corresponding to each flow rate. The table further includes the biogas flow over the specified days, offering insights into the changing methane percentage within the biogas.

Table 4.1: Simulation results for variation in flow rate.

Flow rate (m^3/day)	HRT (days)	Biogas generated (m^3)	Methane percentage
0.4	20	15.58	48.27
0.6	13.3	18.43	48.54
0.8	10	20.47	48.81
1.0	8	21.86	49.08
1.2	7	22.98	48.48
1.4	6.7	22.73	46.94
1.6	5	19.51	45.49
1.8	4.4	20.43	44.76
2.0	4	18.49	43.48
2.2	3.6	The reactor was failed.	

5 Discussion

The chapter includes two discussion parts. Initially, the evaluation of various small-scale biogas technologies, examining their benefits and challenges within the specific context. The following discussion is based on a detailed exploration of the simulation results of the AD process.

5.1 Evaluate AD Technologies

This section focuses on assessing the selected technologies- fixed dome, floating drum, and plug-flow bag based on the literature review according to relevant criteria.

Table 5.1 illustrates the structural characteristics and construction of the chosen biogas technologies.

Table 5.1: Structure and construction of the digesters [35], [36], [67], [68], [69], [70].

Types of Digesters	Structure and construction of the digester
Fixed dome	A sealed structure with a dome-shaped design constructed from reinforced concrete or masonry. It consists of a closed digester in a dome shape, featuring a stationary gas-holder with CSTR type. (see Figure 2.5). Gas holders are a crucial component of the masonry structure of the plant. The slurry, generated from gas formation, is expelled from the gas storage section of the digester and returns when needed. The volume of the digester is 6 - 124 m^3. The construction materials are bricks, cement, concrete, plastic, or reinforced fiber. Easy to construct but needs expertise for airtight construction. It is challenging to build on bedrock. A special sealant is required for the gasholder. Requires more excavation work. Lack of mechanical components.
Floating drum	It is an underground structure comprising a cylindrical or dome-shaped digester, a metallic floating drum or gas holder, an inlet tank, an outlet tank, an inlet pipe, outlet pipe, and a partition wall with a semi-CSTR type (see Figure 2.6). Gas holders are typically constructed from mild steel and are inverted into the digester, moving up and down in response to the generation and utilization of gas. The volume of the digester is up to 20 m^3. Difficult to construct compared to the fixed dome.

	The materials used for the construction are metal (mild steel), reinforced fiber plastics, high-density polyethylene mixed material, bricks, or reinforced concrete used for digester walls. Requires relatively less excavation.
Plug-flow bag	Flexible, elongated bag made of durable, gas-tight materials that facilitate slurry flow from the inlet to the outlet. In the upper section of the digester, biogas is collected through a gas pipe connected to a reservoir with a plug flow type. (see Figure 2-5) The construction materials are reinforced plastics, red mud plastic, and high-strength PVC polyester fabric. Easy to construct.

Table 5.2 indicates the information related to the maintenance of each digester.

Table 5.2: Maintenance of the digesters [67], [69], [70].

Types of Digesters	Maintenance
Fixed dome	It needs less maintenance because of the simple structure. Gas pressure varies. Gas leakage problems can occur frequently. It can be self-agitated by gas pressure.
Floating drum	It needs high maintenance because the gas holder is to be prevented from corrosion. Gas pressure remains constant. The steel drum is relatively expensive and needs regular maintenance. Need manual steering for the agitation.
Plug-flow bag	Need frequent maintenance. Gas pressure varies. Agitation is not possible during the operation. Susceptible to physical damage. Hard to repair.

Table 5.3 shows the lifespan of chosen biogas technologies.

Table 5.3: Life span [69].

Types of Digesters	Lifespan
Fixed dome	long lifespan, up to 20 years
Floating drum	15 years
Plug flow bag	the limited life span of 3-5 years

Table 5.4 indicates the relative cost for each technology.

Table 5.4: Cost [69].

Types of Digesters	Cost
Fixed dome	The fixed dome digester is relatively inexpensive. High material transportation cost. The cost of maintenance is low.
Floating drum	Relatively expensive compare. The cost of maintenance is high.
Plug flow	Relatively very cheap. Material transportation cost is low. The cost of maintenance is very low.

5.2 Simulation of AD Process

This discussion section provides a thorough analysis and interpretation of the simulated results. It thoroughly examines key findings, explores patterns, and provides insights into the performance of the simulated system.

The unavailability of specific data for the Sri Lankan region poses a challenge in accurately representing conditions in Sri Lanka. Apart from this limitation, the collected data from an open-access publication offers valuable insights for ADM1 modeling and guarantees transparency and accessibility to the scientific community.

5.2.1 Gas Flow

In Figure 4.1, the initial absence of gas flow within three days shows a lag phase in biogas production. This phenomenon aligns with the necessary acclimation time for microbes to commence the decomposition of complex organic matter. The following days show a consistent exponential increase in gas flow, peaking at approximately 16.88 m^3. This phase represents the rapid growth to break down the organic substances effectively. After day 40, the gas flow reached a stable state, suggesting an equilibrium in the AD system where the gas production rate meets the decomposition of organic matter. The exponential growth and steady-state phases indicate that the simulated conditions create a favorable condition for efficient biogas production in the reactor.

AD undergoes an initial lag phase, followed by a rapid exponential growth in gas flow until it reaches a stable state [71]. The simulated result aligns with the theoretical expectation, promoting confidence in the model's ability to make predictions.

5.2.2 Adjusted Reactor Gas Pressure

The simulated result of the adjusted gas pressure shows the reactor's CH4, CO2 and H2 percentages in Figure 4.2. When the gas flow exhibited a lag phase (see Figure 4.1), the adjusted gas pressure showed higher rates for CH_4 and CO_2 in the first 1-2 days. This unexpected discrepancy leads to questions regarding the resulting high percentages of CH_4 and CO_2 despite minimal gas flow. Then, the following days show a consistent decrease in CH_4, CO_2, and H_2 percentages, indicating a changing composition of biogas. Beyond 40 days, the adjusted gas pressure stabilizes, indicating the reactor's balanced CH4, CO2 and H2 composition.

During the typical AD, the composition of biogas experiences dynamic fluctuations, with the concentration of CH_4, CO_2, and H_2 altering during various phases [71]. The unexpected increase in the adjusted gas pressure percentage can be related to microbial activity, possibly induced by the breakdown of easily accessible organic matters, even before the commencement of significant gas flow.

5.2.3 pH

The simulated result for pH is illustrated in Figure 4.3. It shows a consistent trend in pH value in the reactor over 70 days, with a gradual decrease from the initial 7.57 to a stabilized value around 7.19. This change in the pH somehow expected a trend in AD. However, there are several notable deviations from the typical AD process. In theoretical AD, the pH decreases during the acidogenesis phase and then stabilizes or slightly increases during methanogenesis [72]. The simulated result contradicts the conventional decrease during acidogenesis, which

deviates from the expected trend. The impact of alkalinity may have had a substantial effect on the simulation, which led to the unexpected trend in the pH in the reactor.

5.2.4 Volatile Fatty Acids

The simulated results for Volatile Fatty Acids (VFA), such as acetate, butyrate, valerate, and propionate concentrations, shown in Figure 4.4, provide valuable insights into microbial metabolic activities.

The initial concentrations of acetate, butyrate, valerate, and propionate show a unique pattern, indicating the production of VFA from organic substrate. Throughout the 70 days, the levels of individual VFAs show fluctuating patterns, indicating the utilization of organic substances by different microbial populations. As the primary VFA, acetate influences the overall composition most.

The simulated result indicates a notable increased acetate level in the reactor, suggesting possible AD process challenges. This increased acetate concentration can be due to reasons such as inadequate microbial activity leading to incomplete conversion of acetate. In addition, the presence of low levels of methanogenic activity, acidogenic conditions that promote the growth of acid-forming bacteria, and high organic loading rates [73], [74].

5.2.5 Biomass

Biomass refers to the total microbial population present in the AD system. The concentration of biomass in the reactor is a crucial parameter. Because it influences the rates of substrate degradation and biogas production. ADM1 uses differential equations to model the dynamic interactions among microbial groups and their reactions to various substrates.

According to Figure 4.5, which shows the simulated biomass concentration in the reactor, sugar-consuming bacteria are the most abundant. Subsequently, an increase in biomass concentration is observed for acetate and H2 degraders. This result aligns with findings from a previous study [75]. A slight upward trend can be noticed for C4 and propionate degrader concentration. In contrast, LCFA and amino acid degrader concentrations slightly decrease over the simulated period.

5.2.6 Inhibition

The simulated results regarding the inhibition reveal the impact of specific factors on microbial degradation processes in the reactor. Especially the effect of H_2 on C4 (Valerate and butyrate) degraders, H_2 on propionate degraders, and NH_3 on acetate degraders. Understanding inhibition activities is vital for identifying the optimal operational conditions and detecting potential issues in the AD system. According to the inhibition scale, a value of 1 represents complete inhibition, while a value of 0 means no inhibition [76].

In the result, a complete inhibition activity is observed concerning the inhibition of pH on H_2 degraders. Initially, both H_2 on C4 degraders and H_2 on propionate degraders show high inhibitory activity, reaching close to 1. This activity then slightly decreases and stabilizes. In contrast, the inhibition activity of NH_3 on acetate degraders shows a relatively lower initial value of 0.6, which indicates an upward trend nearing 0.8 and then remains unchanged.

The simulation suggested that H_2 has varying inhibitory effects on C4 and propionate degraders. Initially high and then gradually decreases, possibly indicating microbial adaptation or the consumption of inhibitory compounds. The simulation shows a relatively stable trend of

NH_3 on acetate degraders after around 5 days. That can be due to the continuous impact of NH_3 on specific microbial populations responsible for acetate degradation.

5.2.7 Additional Data Set

The simulated result from the additional data sets shows a significant variation in gas flow and the adjusted gas pressure compared to the gathered data results. The comparison of these two results from two datasets representing the different input state variable values for the cattle manure substrate.

Accurate determination of cattle manure is essential as it directly impacts the organic matter content, including its specific combination of amino acids, fatty acids, and sugars and the presence of inhibitory chemicals. Precise parameterization is also required to reflect microbial interaction and biochemical reaction complexities fully.

These variations highlight the significance of accurate determination of substrate and the need for proper parameterization to ensure reliable prediction in the AD process.

5.2.8 Variation in Flow Rate

The simulation results clearly show a noticeable trend in the impact of varying flow rates on biogas production and CH_4 percentage in the biogas produced. Initially, a positive correlation was observed, indicating that an increase in the flow rate resulted in higher biogas production and CH_4 percentage. This trend peaked at a flow rate of 1.0 m^3/day, indicating the best performance of the AD system with the highest CH_4 achieved in the simulated conditions.

However, beyond this optimal point, a declining pattern is noticeable. The reactor experienced failure due to a further increase in the flow rate, notably when it reached 2.2 m^3/day. This suggests a possible operational limit or stress condition for the AD reactor in the simulated environment.

Various factors can impact the failure of the reactor beyond a particular point in the simulation. Hydraulic overloading occurs when the substrate inflow exceeds the system's treatment capacity, reducing the retention time for AD. Substrate inhibition worsens the situation and hinders the microorganism from effectively managing the excessive organic load. This has a negative impact on their performance in the AD process. In addition, the rapid increase in flow rate induces acidification, disturbing the pH balance and inhibiting the methane-producing bacteria, which leads to a simultaneous decrease in CH_4 percentage and overall biogas production [73], [74].

6 Conclusion

Biogas obtained from anaerobic digestion is a versatile and environmentally friendly energy source that can be used for heating, electricity production, and agricultural improvement. The evaluation conducted in this study has identified fixed dome, floating drum, and plug-flow bag anaerobic digestion technologies as specifically suitable for small-scale agricultural waste treatment.

The ADM1 model is widely utilized for various purposes, including designing, operating, and optimizing anaerobic digestion. The simulations provide valuable insights into different reactor phases, aiding in identifying limiting factors in the anaerobic digestion process. According to the simulation performed preliminary, the optimal performance of the anaerobic digestion system with a CSTR-type reactor with a volume of 8 m^3, a flow rate of 1.0 m^3/day, and an 8-day hydraulic retention time in simulated conditions resulted in the highest methane percentage.

Future Recommendation

In the future, conducting economic analysis tailored to Sri Lanka's circumstances and focusing on small-scale biogas technologies is essential. This analysis will explore the financial complexities, potential returns, and overall economic feasibility within the unique agricultural context of Sri Lanka.

Proposing possible technological changes based on the technical and economic analysis will contribute to the technology's effectiveness and sustainability.

To enhance the accuracy of the simulated results, utilizing local data in the simulation process is vital as it provides insights into regional economic factors and market dynamics.

References

[1] A. Kosna, 'Design of a Portable Biogas Purification and Storage System', 2018. [Online]. Available: https://scholarworks.wmich.edu/masters_theses

[2] M. M. Maghanaki, B. Ghobadian, G. Najafi, and R. J. Galogah, 'Potential of biogas production in Iran', *Renewable and Sustainable Energy Reviews*, vol. 28. pp. 702–714, 2013. doi: 10.1016/j.rser.2013.08.021.

[3] K. Obaideen *et al.*, 'Biogas role in achievement of the sustainable development goals: Evaluation, Challenges, and Guidelines', *Journal of the Taiwan Institute of Chemical Engineers*, vol. 131. Taiwan Institute of Chemical Engineers, Feb. 01, 2022. doi: 10.1016/j.jtice.2022.104207.

[4] S. Achinas and G. J. W. Euverink, 'Theoretical analysis of biogas potential prediction from agricultural waste', *Resource-Efficient Technologies*, vol. 2, no. 3, pp. 143–147, Sep. 2016, doi: 10.1016/j.reffit.2016.08.001.

[5] 'Application_of_biogas_technology_in_Turk'.

[6] A. Coomaraswamy Mawatha and S. Lanka, 'Sri Lanka Sustainable Energy Authority'.

[7] A. Development Bank, '100% percent Electricity Generation through Renewable Energy by 2050: Assessment of Sri Lanka's Power Sector'.

[8] W. A. M. A. N. Illankoon *et al.*, 'Agricultural Biomass-Based Power Generation Potential in Sri Lanka: A Techno-Economic Analysis', *Energies (Basel)*, vol. 15, no. 23, Dec. 2022, doi: 10.3390/en15238984.

[9] 'Ministry of Power & Energy SRI LANKA ENERGY SECTOR DEVELOPMENT PLAN FOR A KNOWLEDGE-BASED ECONOMY', 2015.

[10] '5_Chapter_01'.

[11] '1687251830Statistical_Digest_2022'.

[12] X. Zhao, L. Li, D. Wu, T. Xiao, Y. Ma, and X. Peng, 'Modified Anaerobic Digestion Model No. 1 for modeling methane production from food waste in batch and semi-continuous anaerobic digestions', *Bioresour Technol*, vol. 271, pp. 109–117, Jan. 2019, doi: 10.1016/j.biortech.2018.09.091.

[13] I. Angelidaki *et al.*, 'Biogas upgrading and utilization: Current status and perspectives', *Biotechnology Advances*, vol. 36, no. 2. Elsevier Inc., pp. 452–466, Mar. 01, 2018. doi: 10.1016/j.biotechadv.2018.01.011.

[14] X. Liu, Z. Yan, and Z. B. Yue, 'Biogas', in *Comprehensive Biotechnology, Second Edition*, vol. 3, Elsevier Inc., 2011, pp. 99–114. doi: 10.1016/B978-0-08-088504-9.00165-3.

[15] 'BIOGAS', 2022. [Online]. Available: www.bioenergyeurope.org

[16] R. Goswami *et al.*, 'An overview of physico-chemical mechanisms of biogas production by microbial communities: A step towards sustainable waste management', *3 Biotech*, vol. 6, no. 1. Springer Verlag, Jun. 01, 2016. doi: 10.1007/s13205-016-0395-9.

[17] I. Koniuszewska, E. Korzeniewska, M. Harnisz, and M. Czatzkowska, 'Intensification of biogas production using various technologies: A review', *International Journal of*

Energy Research, vol. 44, no. 8. John Wiley and Sons Ltd, pp. 6240–6258, Jun. 25, 2020. doi: 10.1002/er.5338.

[18] A. P. T. S. Peiris, 'Feasibility Study of Production of Bio Methane from Bio Wastes in Sri Lanka and Develop Cost Model for the Production Process'.

[19] F. Obi, B. Ugwuishiwu, and J. Nwakaire, 'AGRICULTURAL WASTE CONCEPT, GENERATION, UTILIZATION AND MANAGEMENT', *Nigerian Journal of Technology*, vol. 35, no. 4, p. 957, Sep. 2016, doi: 10.4314/njt.v35i4.34.

[20] Y. Dai *et al.*, 'Utilizations of agricultural waste as adsorbent for the removal of contaminants: A review', *Chemosphere*, vol. 211. Elsevier Ltd, pp. 235–253, Nov. 01, 2018. doi: 10.1016/j.chemosphere.2018.06.179.

[21] L. Pattanaik, F. Pattnaik, D. K. Saxena, and S. N. Naik, 'Biofuels from agricultural wastes', in *Second and Third Generation of Feedstocks: The Evolution of Biofuels*, Elsevier, 2019, pp. 103–142. doi: 10.1016/B978-0-12-815162-4.00005-7.

[22] M. Scherzinger, M. Kaltschmitt, and A. Y. Elbanhawy, 'Anaerobic biogas formation from crops' agricultural residues – Modeling investigations', *Bioresour Technol*, vol. 359, Sep. 2022, doi: 10.1016/j.biortech.2022.127497.

[23] A. Dasgupta and M. K. Chandel, 'Enhancement of biogas production from organic fraction of municipal solid waste using alkali pretreatment', *J Mater Cycles Waste Manag*, vol. 22, no. 3, pp. 757–767, May 2020, doi: 10.1007/s10163-020-00970-2.

[24] S. Luostarinen, S. Luste, and M. Sillanpää, 'Increased biogas production at wastewater treatment plants through co-digestion of sewage sludge with grease trap sludge from a meat processing plant', *Bioresour Technol*, vol. 100, no. 1, pp. 79–85, Jan. 2009, doi: 10.1016/j.biortech.2008.06.029.

[25] S. Mirmohamadsadeghi, K. Karimi, M. Tabatabaei, and M. Aghbashlo, 'Biogas production from food wastes: A review on recent developments and future perspectives', *Bioresour Technol Rep*, vol. 7, Sep. 2019, doi: 10.1016/j.biteb.2019.100202.

[26] Y. Y. Choong, I. Norli, A. Z. Abdullah, and M. F. Yhaya, 'Impacts of trace element supplementation on the performance of anaerobic digestion process: A critical review', *Bioresource Technology*, vol. 209. Elsevier Ltd, pp. 369–379, Jun. 01, 2016. doi: 10.1016/j.biortech.2016.03.028.

[27] S.-Iong. Ao, Craig. Douglas, W. S. Grundfest, Jon. Burgstone, and International Association of Engineers., *World Congress on Engineering and Computer Science : WCECS 2014 : 22-24 October, 2014, San Francisco, USA*.

[28] S. Dayarathna, 'Candidate: Sithara Dayarathna Title: Simulation of Gas and Liquid Flow in a Biogas Reactor Using Fluent'.

[29] P. G. Kougias and I. Angelidaki, 'Biogas and its opportunities—A review', *Front Environ Sci Eng*, vol. 12, no. 3, Jun. 2018, doi: 10.1007/s11783-018-1037-8.

[30] R. A. Labatut, L. T. Angenent, and N. R. Scott, 'Conventional mesophilic vs. thermophilic anaerobic digestion: Atrade-off between performance and stability?', *Water Res*, vol. 53, pp. 249–258, Apr. 2014, doi: 10.1016/j.watres.2014.01.035.

[31] F. Demichelis, T. Tommasi, F. A. Deorsola, D. Marchisio, and D. Fino, 'Effect of inoculum origin and substrate-inoculum ratio to enhance the anaerobic digestion of

organic fraction municipal solid waste (OFMSW)', *J Clean Prod*, vol. 351, Jun. 2022, doi: 10.1016/j.jclepro.2022.131539.

[32] R. Chandra, H. Takeuchi, and T. Hasegawa, 'Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production', *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3. pp. 1462–1476, Apr. 2012. doi: 10.1016/j.rser.2011.11.035.

[33] X. Liu *et al.*, 'Pilot-scale anaerobic co-digestion of municipal biomass waste and waste activated sludge in China: Effect of organic loading rate', *Waste Management*, vol. 32, no. 11, pp. 2056–2060, Nov. 2012, doi: 10.1016/j.wasman.2012.03.003.

[34] M. M. Rahman *et al.*, 'Economics of biogas plants and solar home systems: For household energy applications', *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences Journal homepage*, vol. 33, no. 1, pp. 14–26, 2017, [Online]. Available: www.akademiabaru.com/arfmts.html

[35] M. N. Uddin *et al.*, 'Prospects of Bioenergy Production From Organic Waste Using Anaerobic Digestion Technology: A Mini Review', *Frontiers in Energy Research*, vol. 9. Frontiers Media S.A., Feb. 25, 2021. doi: 10.3389/fenrg.2021.627093.

[36] S. Velmurugan, B. Deepanraj, and S. Jayaraj, ') May (2014) Res'. [Online]. Available: https://www.researchgate.net/publication/262033577

[37] T. T. Olugasa, I. F. Odesola, and M. O. Oyewola, 'Energy production from biogas: A conceptual review for use in Nigeria', *Renewable and Sustainable Energy Reviews*, vol. 32. pp. 770–776, Apr. 2014. doi: 10.1016/j.rser.2013.12.013.

[38] M. Pilloni, T. A. Hamed, M. Pilloni, and T. A. Hamed, 'Small-Size Biogas Technology Applications for Rural Areas in the Context of Developing Countries', *Anaerobic Digestion in Built Environments*, Mar. 2021, doi: 10.5772/INTECHOPEN.96857.

[39] 'Backyard Biogas Production from Animal Manure: Process and Utilization | UNL Water'. Accessed: Dec. 13, 2023. [Online]. Available: https://water.unl.edu/article/animal-manure-management/backyard-biogas-production-animal-manure-process-and-utilization

[40] A. Perez Garcia, 'Techno-economic feasibility study of a small-scale biogas plant for treating market waste in the city of El Alto'.

[41] G. Glivin, M. Vairavan, P. Manickam, and J. S. Santhappan, 'Techno Economic Studies on the Effective Utilization of Non-Uniform Biowaste Generation for Biogas Production'. [Online]. Available: www.intechopen.com

[42] K. Rajendran, S. Aslanzadeh, and M. J. Taherzadeh, 'Household biogas digesters-A review', *Energies*, vol. 5, no. 8. MDPI AG, pp. 2911–2942, 2012. doi: 10.3390/en5082911.

[43] S. Banerjee, N. Prasad, and S. Selvaraju, 'Reactor Design for Biogas Production-A Short Review', *Journal of Energy and Power Technology*, vol. 4, no. 1, pp. 1–1, Sep. 2021, doi: 10.21926/jept.2201004.

[44] A. Dutta, C. Davies, and D. S. Ikumi, 'Performance of upflow anaerobic sludge blanket (UASB) reactor and other anaerobic reactor configurations for wastewater treatment: A comparative review and critical updates', *Journal of Water Supply:*

Research and Technology - AQUA, vol. 67, no. 8. IWA Publishing, pp. 858–884, Dec. 01, 2018. doi: 10.2166/aqua.2018.090.

[45] K. Svensson, *Improving food waste anaerobic digestion: effects of digestate recirculation, post-treatment and methane-methane serial digestion*.

[46] J. Ariunbaatar, A. Panico, G. Esposito, F. Pirozzi, and P. N. L. Lens, 'Pretreatment methods to enhance anaerobic digestion of organic solid waste', *Applied Energy*, vol. 123. Elsevier Ltd, pp. 143–156, Jun. 15, 2014. doi: 10.1016/j.apenergy.2014.02.035.

[47] T. Forster-Carneiro, R. Isaac, M. Pérez, and C. Schvartz, 'Anaerobic Digestion Pretreatments of Substrates'. [Online]. Available: http://ebookcentral.proquest.com/lib/ucsn-ebooks/detail.action?docID=875912.

[48] L. Deng, Y. Liu, and W. Wang, *Biogas technology*. Springer Singapore, 2020. doi: 10.1007/978-981-15-4940-3.

[49] M. Prussi, M. Padella, M. Conton, E. D. Postma, and L. Lonza, 'Review of technologies for biomethane production and assessment of Eu transport share in 2030', *J Clean Prod*, vol. 222, pp. 565–572, Jun. 2019, doi: 10.1016/j.jclepro.2019.02.271.

[50] X. Y. Chen, H. Vinh-Thang, A. A. Ramirez, D. Rodrigue, and S. Kaliaguine, 'Membrane gas separation technologies for biogas upgrading', *RSC Advances*, vol. 5, no. 31. Royal Society of Chemistry, pp. 24399–24448, 2015. doi: 10.1039/c5ra00666j.

[51] S. Sahota *et al.*, 'Review of trends in biogas upgradation technologies and future perspectives', *Bioresource Technology Reports*, vol. 1. Elsevier Ltd, pp. 79–88, Mar. 01, 2018. doi: 10.1016/j.biteb.2018.01.002.

[52] W. M. Budzianowski and M. Brodacka, 'Biomethane storage: Evaluation of technologies, end uses, business models, and sustainability', *Energy Convers Manag*, vol. 141, pp. 254–273, 2017, doi: 10.1016/j.enconman.2016.08.071.

[53] I. Ullah Khan *et al.*, 'Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage', *Energy Conversion and Management*, vol. 150. Elsevier Ltd, pp. 277–294, 2017. doi: 10.1016/j.enconman.2017.08.035.

[54] T. He *et al.*, 'Black Hole-Inspired Optimal Design of Biomethane Liquefaction Process for Small-Scale Applications', *Front Energy Res*, vol. 9, Apr. 2021, doi: 10.3389/fenrg.2021.656165.

[55] E. Twinomunuji *et al.*, 'The potential for bottled biogas for clean cooking in Africa The potential for bottled biogas for clean cooking in Africa The potential for bottled biogas for clean cooking in Africa'. [Online]. Available: https://www.mecs.org.uk/working-papers/.3

[56] C. Herbes, V. Halbherr, and L. Braun, 'Factors influencing prices for heat from biogas plants', *Appl Energy*, vol. 221, pp. 308–318, Jul. 2018, doi: 10.1016/j.apenergy.2018.03.188.

[57] H. M. Morgan *et al.*, 'A techno-economic evaluation of anaerobic biogas producing systems in developing countries', *Bioresource Technology*, vol. 250. Elsevier Ltd, pp. 910–921, Feb. 01, 2018. doi: 10.1016/j.biortech.2017.12.013.

[58] T. Zhang, Y. Yang, and D. Xie, 'Insights into the production potential and trends of China's rural biogas', *International Journal of Energy Research*, vol. 39, no. 8. John Wiley and Sons Ltd, pp. 1068–1082, Jun. 25, 2015. doi: 10.1002/er.3311.

[59] H. Roubík and J. Mazancová, ‘Small-and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers’, 2016.

[60] M. Bekchanov, M. A. H. Mondal, A. de Alwis, and A. Mirzabaev, ‘Why adoption is slow despite promising potential of biogas technology for improving energy security and mitigating climate change in Sri Lanka?’, *Renewable and Sustainable Energy Reviews*, vol. 105, pp. 378–390, May 2019, doi: 10.1016/j.rser.2019.02.010.

[61] H. Roubík and J. Mazancová, ‘Small-and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers’, 2016.

[62] D. J. Batstone, I. Angelidaki, and V. Vavilin, ‘Anaerobic digestion model No 1 (ADM1) ARC discovery grant View project Metabolic Mechanisms and Regulation of Mixed Culture Fermentation View project’, 2002. [Online]. Available: https://www.researchgate.net/publication/11198259

[63] L. Andrea, M. García, Á. David, R. Vargas, H. Enrique, and R. Cubides, ‘COMPUTATIONAL MODEL OF AN ELECTRIC POWER GENERATION SYSTEM BASED ON BIOGAS OBTAINED FROM CATTLE MANUREODELO-847X’. [Online]. Available: http://itcelaya.edu.mx/ojs/index.php/pistas

[64] Z. Xu, S. Dr, T. M. Louw Co-Supervisor, and A. J. Burger, ‘ADM1 Parameter Calibration Method based on Partial Least Squares Regression Framework for Industrial-scale Anaerobic Digestion Modelling’, 2019. [Online]. Available: https://scholar.sun.ac.za

[65] L. A. Morales, A. D. Rodriguez, and H. E. Rojas, ‘Assessment of the Input Substrate Characteristics Included in the Anaerobic Digestion Model No. 1 (ADM1)’, *Ingeniería*, vol. 22, no. 2, p. 269, May 2017, doi: 10.14483/udistrital.jour.reving.2017.2.a07.

[66] H. Fisgativa, B. Zennaro, C. Charnier, C. Richard, G. Accarion, and F. Béline, ‘Comprehensive determination of input state variables dataset required for anaerobic digestion modelling (ADM1) based on characterisation of organic substrates’, *Data Brief*, vol. 29, Apr. 2020, doi: 10.1016/j.dib.2020.105212.

[67] ‘Comparison_among_different_models_of_biogas_plant’.

[68] K. C. Obileke, H. Onyeaka, and N. Nwokolo, ‘Materials for the design and construction of household biogas digesters for biogas production: A review’, *International Journal of Energy Research*, vol. 45, no. 3. John Wiley and Sons Ltd, pp. 3761–3779, Mar. 10, 2021. doi: 10.1002/er.6120.

[69] U. Balasubramaniyam, L. S. Zisengwe, N. Meriggi, and E. Buysman, ‘Biogas production in climates with long cold winters’, 2008. [Online]. Available: www.wecf.eu

[70] ‘Fixed-dome Biogas Plants - energypedia’. Accessed: Dec. 13, 2023. [Online]. Available: https://energypedia.info/wiki/Fixed-dome_Biogas_Plants

[71] B. Deepanraj, V. Sivasubramanian, and S. Jayaraj, ‘Effect of substrate pretreatment on biogas production through anaerobic digestion of food waste’, *Int J Hydrogen Energy*, vol. 42, no. 42, pp. 26522–26528, Oct. 2017, doi: 10.1016/j.ijhydene.2017.06.178.

[72] L. Yang *et al.*, ‘Enhancing biogas generation performance from food wastes by high-solids thermophilic anaerobic digestion: Effect of pH adjustment’, *Int Biodeterior Biodegradation*, vol. 105, pp. 153–159, Nov. 2015, doi: 10.1016/j.ibiod.2015.09.005.

[73] M. Westerholm, J. Moestedt, and A. Schnürer, ‘Biogas production through syntrophic acetate oxidation and deliberate operating strategies for improved digester performance’, *Applied Energy*, vol. 179. Elsevier Ltd, pp. 124–135, Oct. 01, 2016. doi: 10.1016/j.apenergy.2016.06.061.

[74] S. Wainaina, Lukitawesa, M. Kumar Awasthi, and M. J. Taherzadeh, ‘Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: A critical review’, *Bioengineered*, vol. 10, no. 1. Taylor and Francis Inc., pp. 437–458, Jan. 01, 2019. doi: 10.1080/21655979.2019.1673937.

[75] Z. Nikbakht Kenarsari, N. Ghimire, R. Bakke, and W. Hennie Bergland, ‘Thermophilic Anaerobic Digestion Modeling of Lignocellulosic Hot Water Extract using ADM1’, in *Proceedings of The 60th SIMS Conference on Simulation and Modelling SIMS 2019, August 12-16, Västerås, Sweden*, Linköping University Electronic Press, Jan. 2020, pp. 125–131. doi: 10.3384/ecp20170125.

[76] S. Astals, M. Peces, D. J. Batstone, P. D. Jensen, and S. Tait, ‘Characterising and modelling free ammonia and ammonium inhibition in anaerobic systems’, *Water Res*, vol. 143, pp. 127–135, Oct. 2018, doi: 10.1016/j.watres.2018.06.021.

Appendices

Appendix A – Kinetic rate equations [62].

Process no	Process	Rate (ρ_j, kg COD.m^{-3}. d^{-1})
1	Disintegration	$k_{dis}X_c$
2	Hydrolysis Carbohydrates	$k_{hyd,ch}X_{ch}$
3	Hydrolysis of Protein	$k_{hyd,pr}X_{pr}$
4	Hydrolysis of Lipids	$k_{hyd,li}X_{li}$
5	Uptake of Sugars	$k_{m,su}\frac{S_{su}}{K_s+S_{su}}X_{su}I_1$
6	Uptake of Amino Acids	$k_{m,aa}\frac{S_{aa}}{K_s+S_{aa}}X_{aa}I_1$
7	Uptake of LCFA	$k_{m,fa}\frac{S_{fa}}{K_s+S_{fa}}X_{fs}I_2$
8	Uptake of Valerate	$k_{m,c4}\frac{S_{va}}{K_s+S_{va}}X_{c4}\frac{1}{1+S_{bu}/S_{va}}I_2$
9	Uptake of Butyrate	$k_{m,c4}\frac{S_{bu}}{K_s+S_{bu}}X_{c4}\frac{1}{1+S_{va}/S_{bu}}I_2$
10	Uptake of Propionate	$k_{m,pro}\frac{S_{pro}}{K_s+S_{pro}}X_{pro}I_2$
11	Uptake of Acetate	$k_{m,ac}\frac{S_{ac}}{K_S+S_{ac}}X_{ac}I_3$
12	Uptake of Hydrogen	$k_{m,h2}\frac{S_{h2}}{K_s+S_{h2}}X_{h2}I_2$
13	Decay of X_{su}	$k_{dec}X_{su}$
14	Decay of X_{aa}	$k_{dec}X_{aa}$
15	Decay of X_{fa}	$k_{dec}X_{fa}$
16	Decay of X_{c4}	$k_{dec}X_{c4}$
17	Decay of X_{pro}	$k_{dec}X_{pro}$
18	Decay of X_{ac}	$k_{dec}X_{ac}$
19	Decay of X_{h2}	$k_{dec}X_{h2}$
Inhibition factors: $I_1 = I_{pH}I_{IN,lim}$ $I_1 = I_{pH}I_{IN,lim}I_{h2}$ $I_1 = I_{pH}I_{IN,lim}I_{NH_3,X_{ac}}$		

Appendix B - Biochemical rate coefficients for soluble components ($\nu_{i,j}$) [62].

Component→	**i**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
j	**Process ↓**	S_{su}	S_{aa}	S_{fa}	S_{va}	S_{bu}	S_{pro}	S_{ac}	S_{h2}	S_{ch4}	S_{IC}	S_{IN}	S_I
1	Disintegration												$f_{sI,xc}$
2	Hydrolysis Carbohydrates	1											
3	Hydrolysis of Protein		1										
4	Hydrolysis of Lipids	1- $f_{fa,li}$		$f_{fa,li}$									
5	Uptake of Sugars	-1				$(1-Y_{su})\ f_{bu,su}$	$(1-Y_{su})\ f_{pro,su}$	$(1-Y_{su})\ f_{ac,su}$	$(1-Y_{su})\ f_{h2,su}$		$-\sum_{i=1-9,11-24} C_i \nu_{i,5}$	$-(Y_{su})N_{bac}$	
6	Uptake of Amino Acids		-1		$(1-Y_{aa})\ f_{va,aa}$	$(1-Y_{aa})\ f_{bu,aa}$	$(1-Y_{aa})\ f_{pro,aa}$	$(1-Y_{aa})\ f_{ac,aa}$	$(1-Y_{aa})\ f_{h2,aa}$		$-\sum_{i=1-9,11-24} C_i \nu_{i,6}$	$N_{aa} - (Y_{aa})\ N_{bac}$	
7	Uptake of LCFA			-1				$(1-Y_{fa})$ 0.7	$(1-Y_{fa})$ 0.3			$-(Y_{fa})N_{bac}$	
8	Uptake of Valerate				-1		$(1-Y_{c4})$ 0.54	$(1-Y_{c4})$ 0.31	$(1-Y_{c4})$ 0.15			$-(Y_{c4})N_{bac}$	
9	Uptake of Butyrate					-1		$(1-Y_{c4})$ 0.8	$(1-Y_{c4})$ 0.2			$-(Y_{c4})N_{bac}$	
10	Uptake of Propionate						-1	$(1-Y_{pro})$ 0.57	$(1-Y_{pro})$ 0.43		$-\sum_{i=1-9,11-24} C_i \nu_{i,10}$	$-(Y_{pro})N_{bac}$	
11	Uptake of Acetate							-1		$(1-Y_{ac})$	$-\sum_{i=1-9,11-24} C_i \nu_{i,11}$	$-(Y_{ac})N_{bac}$	
12	Uptake of Hydrogen								-1	$(1-Y_{h2})$	$-\sum_{i=1-9,11-24} C_i \nu_{i,12}$	$-(Y_{h2})N_{bac}$	
13	Decay of X_{su}												
14	Decay of X_{aa}												
15	Decay of X_{fa}												
16	Decay of X_{c4}												
17	Decay of X_{pro}												
18	Decay of X_{ac}												
19	Decay of X_{h2}												
		Monosaccharides (kgCOD m^{-3})	Amino Acids (kgCOD m^{-3})	Long chain fatty acid (kgCOD m^{-3})	Total valerate (kgCOD m^{-3})	Total butyrate (kgCOD m^{-3})	Total propionate (kgCOD m^{-3})	Total acetate (kgCOD m^{-3})	Hydrogen gas (kgCOD m^{-3})	Methane gas (kgCOD m^{-3})	Inorganic carbon (kmoleC m^{-3})	Inorganic nitrogen (kmoleN m^{-3})	Soluble inserts (kgCOD m^{-3})

Appendix C - Biochemical rate coefficients for particulate components ($\nu_{i,j}$) [62].

Component→	**i**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
j	**Process ↓**	X_c	X_{ch}	X_{pr}	X_{li}	X_{su}	X_{aa}	X_{fa}	X_{c4}	X_{pro}	X_{ac}	X_{h2}	X_I
1	Disintegration	-1	$f_{ch,xc}$	$f_{pr,xc}$	$f_{li,xc}$								$f_{xI,xc}$
2	Hydrolysis Carbohydrates		-1										
3	Hydrolysis of Protein			-1									
4	Hydrolysis of Lipids				-1								
5	Uptake of Sugars					Y_{su}							
6	Uptake of Amino Acids						Y_{aa}						
7	Uptake of LCFA							Y_{fa}					
8	Uptake of Valerate								Y_{c4}				
9	Uptake of Butyrate								Y_{c4}				
10	Uptake of Propionate									Y_{pro}			
11	Uptake of Acetate										Y_{ac}		
12	Uptake of Hydrogen											Y_{h2}	
13	Decay of X_{su}	1				-1							
14	Decay of X_{aa}	1					-1						
15	Decay of X_{fa}	1						-1					
16	Decay of X_{c4}	1							-1				
17	Decay of X_{pro}	1								-1			
18	Decay of X_{ac}	1									-1		
19	Decay of X_{h2}	1										-1	
		Composites (kgCOD m^{-3})	Carbohydrates (kgCOD m^{-3})	Proteins (kgCOD m^{-3})	Lipids (kgCOD m^{-3})	Sugar degraders (kgCOD m^{-3})	Amino acid degraders (kgCOD m^{-3})	LCFA degraders (kgCOD m^{-3})	Valerate and butyrate degraders (kgCOD m^{-3})	Propionate degraders (kgCOD m^{-3})	Acetate degraders (kmoleC m^{-3})	Hydrogen degraders (kmoleN m^{-3})	Particulate degraders (kgCOD m^{-3})

Appendix D - Physico-chemical and biochemical characteristics of cattle manure used to define the input state variable for ADM1 in this study [66].

Parameter	**Unit**	**Values**
pH		8.54
Total solids - TS	$gTS \cdot kgWW^{-1}$	191.3
Volatile solids - VS	$gVS \cdot kgWW^{-1}$	155.7
Total chemical oxygen demand - COD_{tot}	$gO_2 \cdot kgWW^{-1}$	243.1
Total carbon content - TC	$gC \cdot kgWW^{-1}$	79.6
Total inorganic carbon content - TIC	$gC \cdot kgWW^{-1}$	1.2
Total Kjeldahl nitrogen - TKN	$gN \cdot kgWW^{-1}$	5.2
NH^{4+}	$gN \cdot kgWW^{-1}$	0.8
P_{tot}	$gP \cdot kgWW^{-1}$	1.22
K_{tot}	$gK \cdot kgWW^{-1}$	9.02
Lipids	%COD	4.7%
Proteins	%COD	16.2%
Carbohydrates	%COD	79.1%
Biochemical methane potential - BMP	$NLCH_4 \cdot kgWW^{-1}$	39.6
Biological Nitrogen potential – BNP	$gN \cdot kgWW^{-1}$	0.43
Volatile fatty acids - VFA	$gVFA \cdot kgWW^{-1}$	0.00