Design of Indigenous Small Scale Low-Cost Tubular Biogas Digester with Portable Container Box

By

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Session 2021-23

Supervised by

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THESIS ACCEPTANCE CERTIFICATE

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Abstract

This research addresses Pakistan's energy crisis and its impact on small households by proposing an Indigenous Small Scale Low-Cost Tubular Biogas Digester within a Portable Container Box. The compact digester is designed to meet the energy needs of small households, a critical improvement over larger models available in the market. Housed within a specially designed portable container box for easy installation, portability, and protection, this solution aims to overcome the limited availability of suitable tubular biogas digesters in Pakistan, particularly for small rural households.

The Tubular Biogas Digester's theoretical output of 0.43 m^3 per day surpasses the 0.42 m^3 peak output of the compared pseudo dome biogas digester, underscoring the enhanced viability of the proposed solution.

Moreover, financial viability is confirmed through several key indicators. The Net Present Value (NPV) of Rs 5,526.18, calculated with an 8% discount rate, signifies that expected cash inflows from the project surpass initial investment costs, establishing its feasibility. The Return on Investment (ROI) of 15.95% demonstrates robust profitability relative to project costs. The Discounted Payback Period (DPP) of 9.05 years, well within the 10-year project lifespan, suggests not only the recovery of the initial investment but also positive cash flows in the future. The Internal Rate of Return (IRR) at 9.5%, exceeding the discount rate, further reinforces financial feasibility and positive returns.

Keywords: Tubular Biogas Digester, Indigenous, Pakistan, Portable, Mathematical Iteration Modeling, Protective Container Box, Trench Optimization

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Muhammad Ajdar Aneeq Malik, Rabia Liaquat, Adeel Waqas Ahmed, Nadia Shahzad, Majid Ali, "Design of a Low-Cost Tubular Biogas Digester with Portable Container Box."

Journal: Agricultural Research. 2023 (**Under Review**)

Chapter 1: Introduction

1.1 The Scourge of Fossil Fuels

Fossil fuels are non-renewable sources of energy that have been formed over millions of years from the remains of dead plants and animals. These fuels, which include coal, oil, and natural gas, are used extensively around the world to power homes, businesses, and industries. According to the International Energy Agency (IEA), fossil fuels account for 84% of the world's primary energy supply in 2020. Coal remains the largest source of electricity generation worldwide, followed by natural gas and then oil.

The widespread use of fossil fuels is due to their high energy density, which makes them ideal for producing large amounts of energy. Fossil fuels are also relatively easy to transport and store, making them accessible to consumers around the world. However, the use of fossil fuels has several disadvantages, including their negative impact on the environment.

One of the most significant disadvantages of fossil fuels is their contribution to climate change. The burning of fossil fuels releases greenhouse gases, such as carbon dioxide, into the atmosphere. These gases trap heat from the sun, causing the Earth's temperature to rise and leading to a wide range of environmental and social impacts. According to the IEA, the energy sector accounted for around 75% of global greenhouse gas emissions in 2019, with most of those emissions coming from the combustion of fossil fuels [1].

In addition to climate change, fossil fuels have detrimental effects on air quality. The extraction, transportation, and combustion processes release various air pollutants, including sulfur dioxide (SO2), nitrogen oxides (NOx), and particulate matter. These pollutants contribute to air pollution, which has severe implications for human health. Exposure to these pollutants can lead to respiratory problems, cardiovascular diseases, and other adverse health effects, particularly in areas near fossil fuel power plants or highly industrialized regions. [3][5]

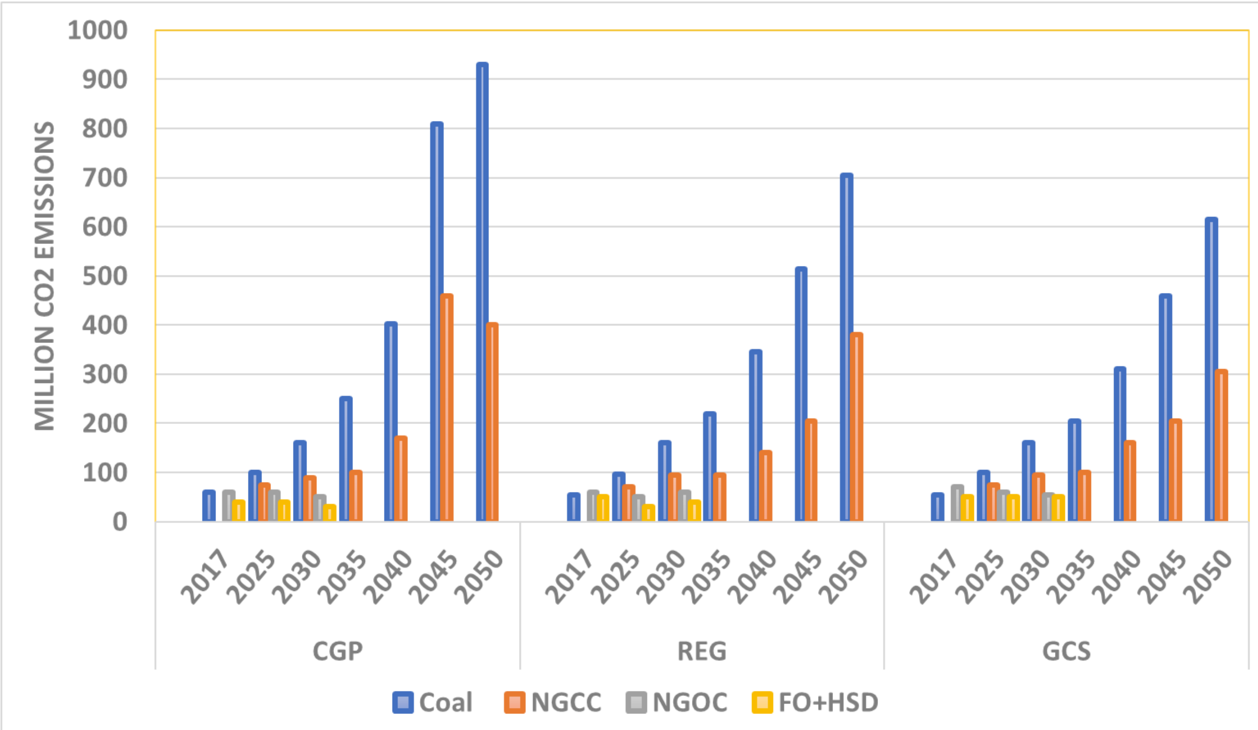

Figure 1-1. Increase in CO2 emissions due to conventional fossil fuel industries [5]

Moreover, the extraction and processing of fossil fuels can result in significant environmental damage. Coal mining, for example, often involves mountaintop removal or underground mining, which can lead to habitat destruction, soil erosion, and water contamination. Oil spills from offshore drilling or pipeline accidents can cause devastating ecological disasters, polluting water bodies and harming marine life. Fracking, a method used to extract natural gas, has been linked to water contamination and the release of methane, a potent greenhouse gas. [3]

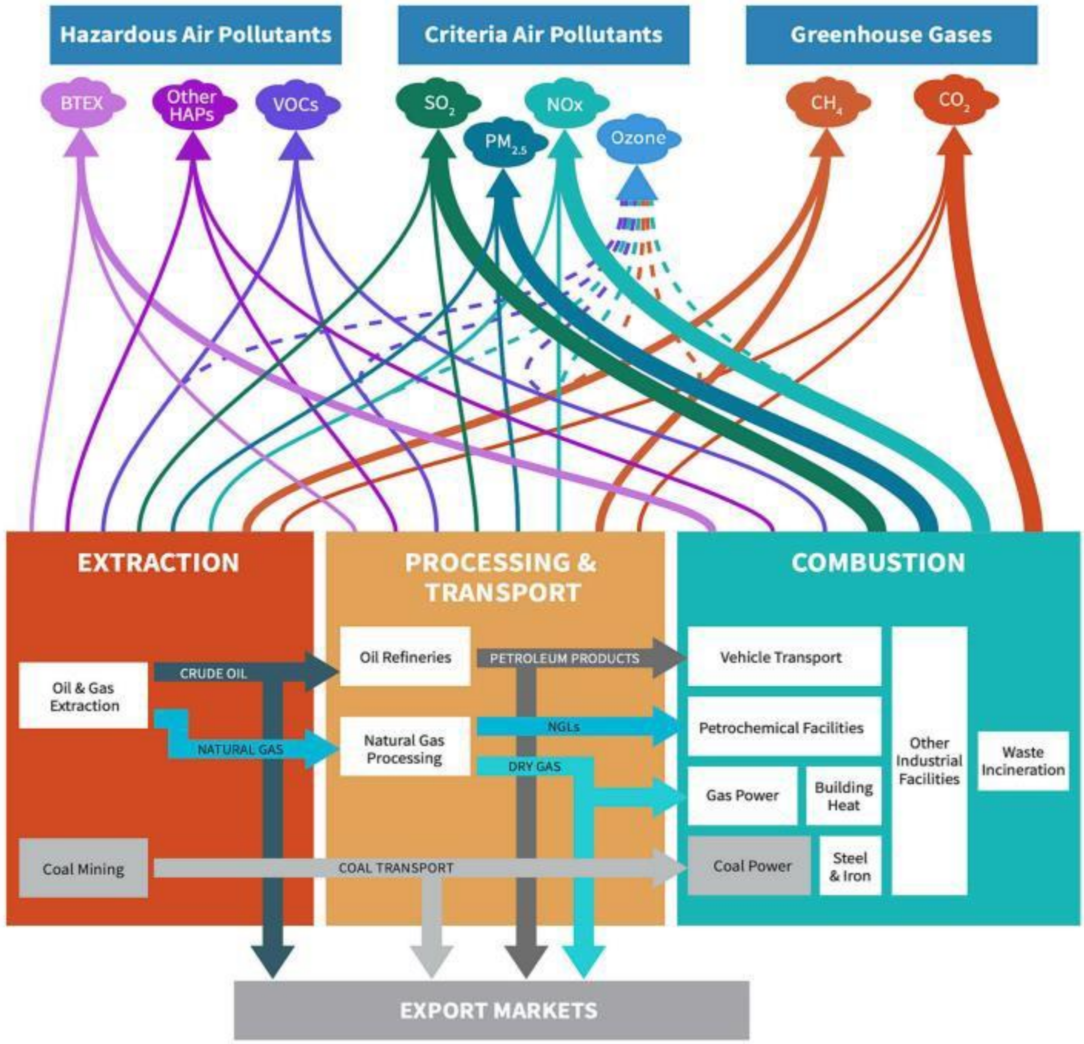

Figure 1-2. Production of harmful gases due to different stages of fossil fuel extraction [3]

Fossil fuels also pose geopolitical and economic challenges. Their finite nature means that as reserves are depleted, the competition for remaining resources intensifies, potentially leading to conflicts. Additionally, the price volatility of fossil fuels can have adverse economic impacts, affecting energy prices, transportation costs, and the stability of economies heavily reliant on fossil fuel exports [4][7].

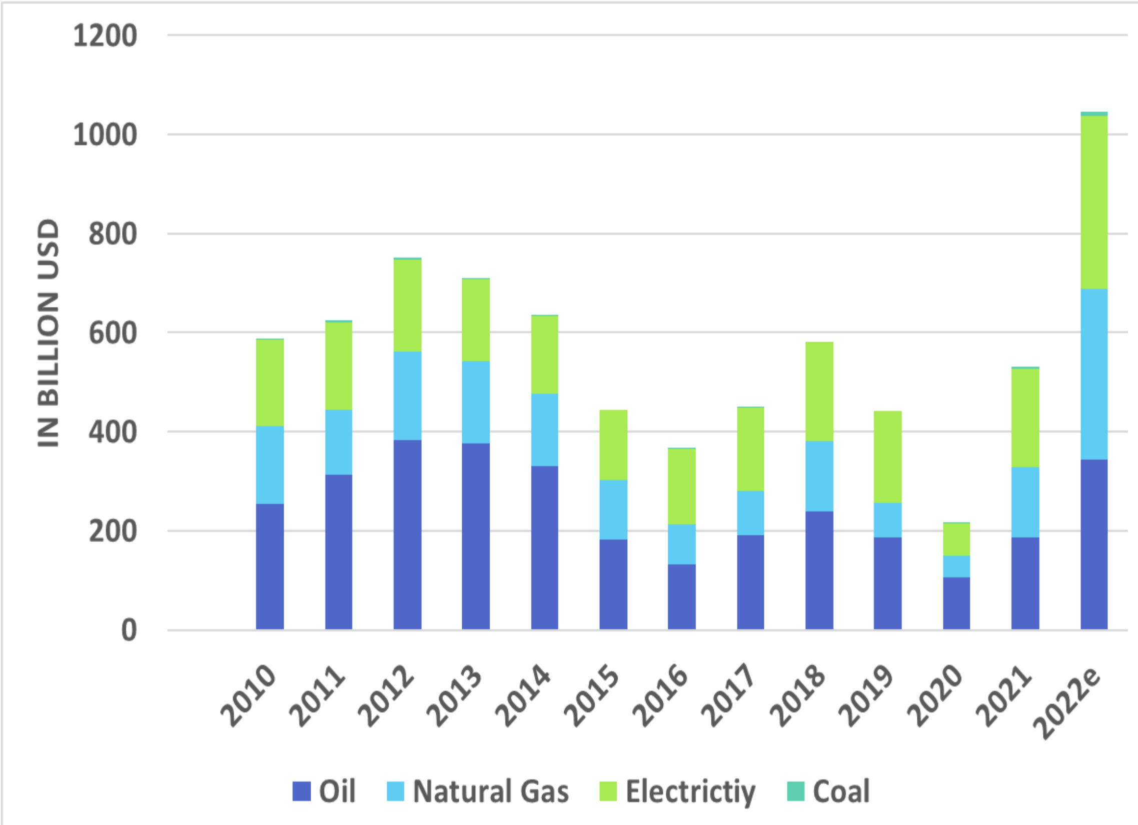

Figure 1-3. Increase in fossil fuel subsidies charted from 2010 to 2022 [4]

Despite these disadvantages, the use of fossil fuels is likely to continue for the foreseeable future, particularly in developing countries seeking to industrialize and improve their living standards. However, there is growing interest in alternative, greener forms of energy production, which can reduce the environmental impacts of energy consumption.

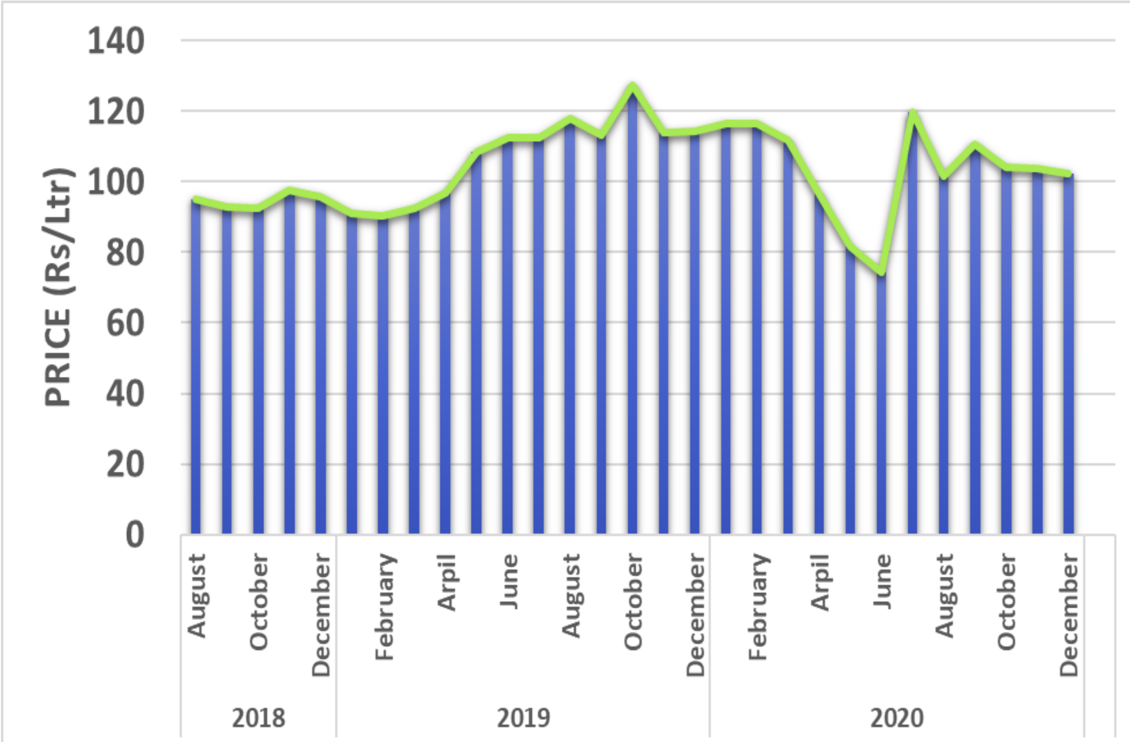

Figure 1-4. Oil price fluctuations in Pakistan from August 2018 to December 2020 [7]

Considering these disadvantages, there is a growing urgency to transition to renewable energy sources. Renewable energy sources, such as solar, wind, and hydropower, are becoming more prevalent as the technology to harness them becomes more efficient and cost-effective. According to the IEA, renewable energy sources accounted for 13.8% of the global primary energy supply in 2019, with hydropower being the largest contributor followed by wind and solar [2].

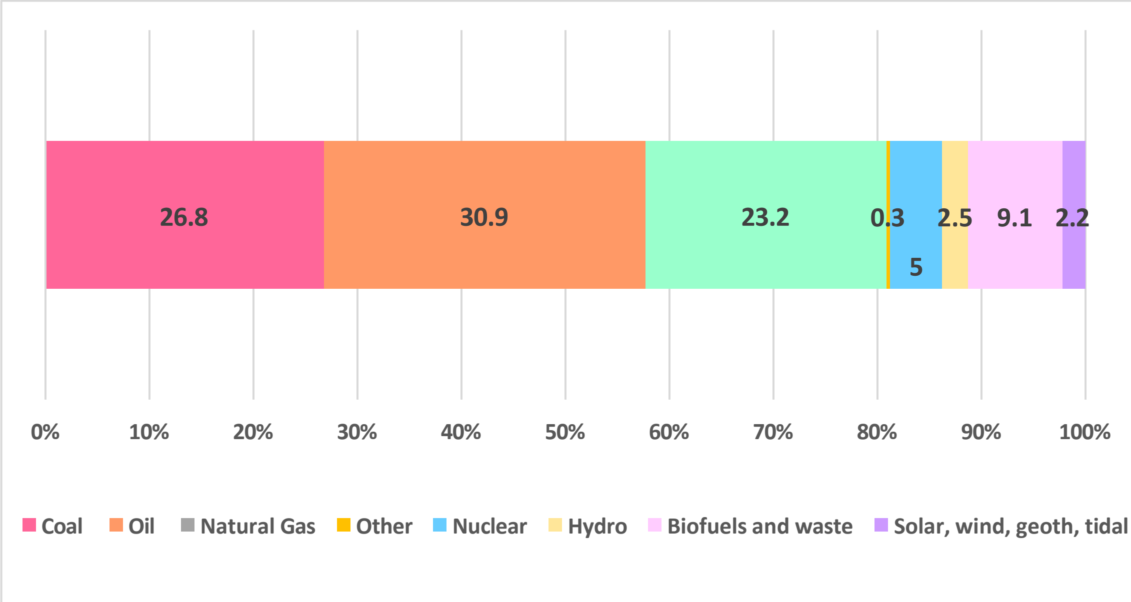

Figure 1-5. Chart for fuel share for total energy supply, 2019 [2]

However, renewable energy sources are not without their challenges. For example, the intermittent nature of solar and wind power means that they are not always available when they are needed, which can make it difficult to balance energy supply and demand. In addition, the construction of renewable energy infrastructure can have its environmental impacts, such as habitat destruction and land use changes.

While the transition to renewable energy presents challenges of its own, such as intermittent and initial infrastructure costs, ongoing advancements in technology and increased investment are addressing these issues. Despite the disadvantages associated with fossil fuels, the adoption of renewable energy sources is crucial for a sustainable and resilient future.

1.2 Energy Crisis in Pakistan

The energy crisis in Pakistan is a multifaceted and persistent issue that has plagued the country for many years, causing significant detrimental effects on its economy, agriculture, industry, and overall societal well-being. At the heart of this crisis lies a substantial disparity between the demand for energy and its available supply, resulting in frequent power outages, load shedding, and blackouts that disrupt daily life for the population.

Several interconnected factors contribute to the energy crisis in Pakistan. Firstly, the nation heavily relies on non-renewable energy sources, particularly oil and gas. According to statistics, as of 2021, Pakistan's energy mix was predominantly composed of fossil fuels, with around 64% of electricity generation dependent on oil and gas. These resources are finite and depleting, leading to a scarcity in energy supply. Pakistan's dependence on these non-renewable sources has hindered its ability to meet the ever-increasing demand for energy [5].

Secondly, inadequate planning and coordination in energy production have contributed to the crisis. Insufficient attention to developing new energy sources and infrastructure has further exacerbated the shortage of energy supply, perpetuating the crisis [5]. According to the World Bank, Pakistan's energy supply is not meeting the demand, with an estimated demand-supply gap of around 5,000 to 6,000 megawatts.

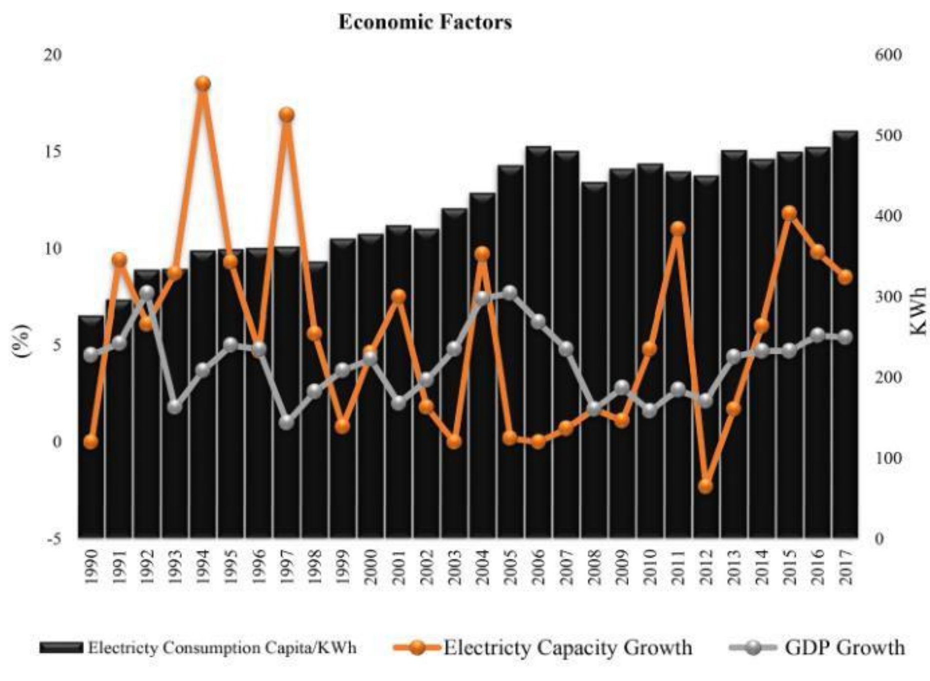

Figure 1-6. Comparison of the electrical consumption and GDP growth diaspora [5]

Additionally, despite being the sixth atomic power globally, Pakistan has not fully harnessed the potential of nuclear energy, thus failing to tap into a substantial energy resource that could help alleviate the crisis. Nuclear power only contributes around 10.6% of the total electricity generation in Pakistan, according to the International Atomic Energy Association [6]. Expanding the utilization of nuclear energy could significantly enhance the energy supply and reduce the dependency on fossil fuels.

To tackle the energy crisis, the government of Pakistan has implemented various measures, although their effectiveness has been limited. One approach has involved the construction of new power plants to augment energy generation capacity. According to the Ministry of Energy (Power Division), the government aims to add around 10,400 megawatts of electricity to the national grid by 2025 through the installation of new power plants. Furthermore, there have been efforts to promote the use of renewable energy sources, such as solar and wind power, as a more sustainable alternative. As of 2020, renewable energy accounted for approximately 4% of Pakistan's electricity generation [8].

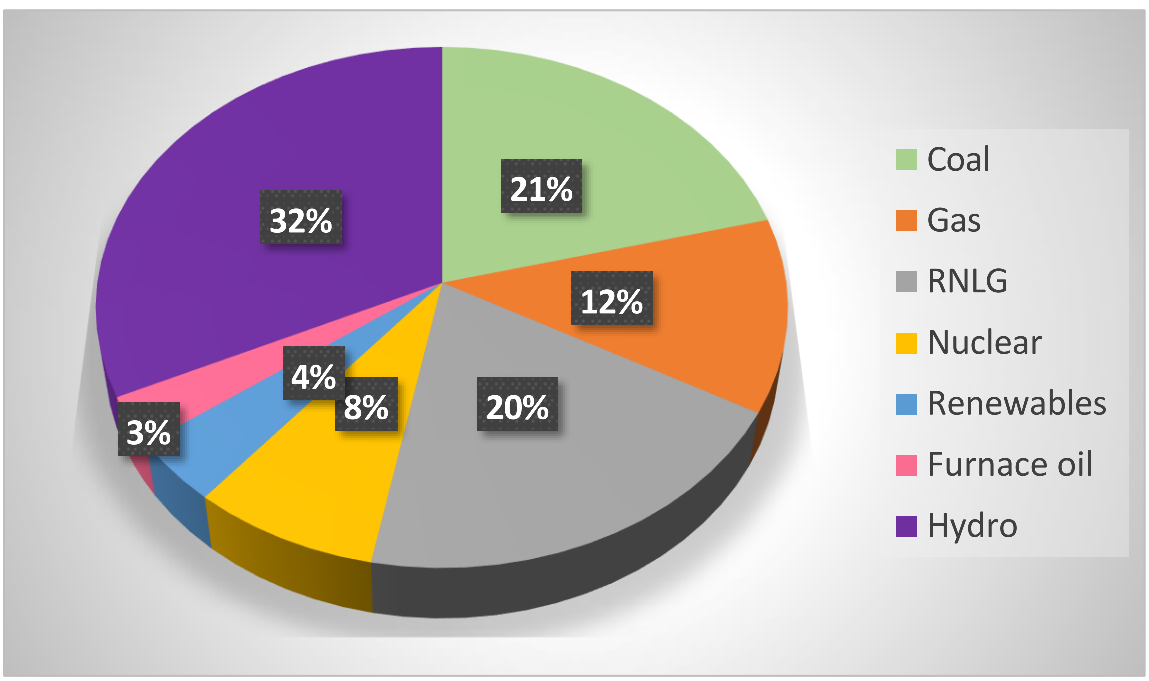

Figure 1-7. Total Energy Mix of Pakistan for the year 2020 [8]

Additionally, improving energy efficiency through the adoption of energy-saving technologies and practices has been prioritized. Keeping in mind Pakistan’s agrarian economy base, one of the most abundant energy resources is Biogas production and manipulation.

1.3 Pakistan’s Potential

Pakistan, with its diverse geographical features and abundant natural resources, possesses immense renewable energy potential. The country's renewable energy sector has been gaining traction in recent years, driven by a combination of government initiatives, international collaborations, and growing awareness of the need to transition to cleaner energy sources.

Solar energy is one of the most promising renewable resources in Pakistan. The country receives abundant sunlight throughout the year, making it highly suitable for solar power generation. Pakistan has the potential to generate over 2.9 million GWh of electricity from solar energy [7]. To tap into this potential, the government has implemented various policies and incentives to promote solar installations, including net metering, feed-in tariffs, and tax exemptions. Several large-scale solar projects have already been commissioned, and the country aims to increase its solar capacity significantly in the coming years.

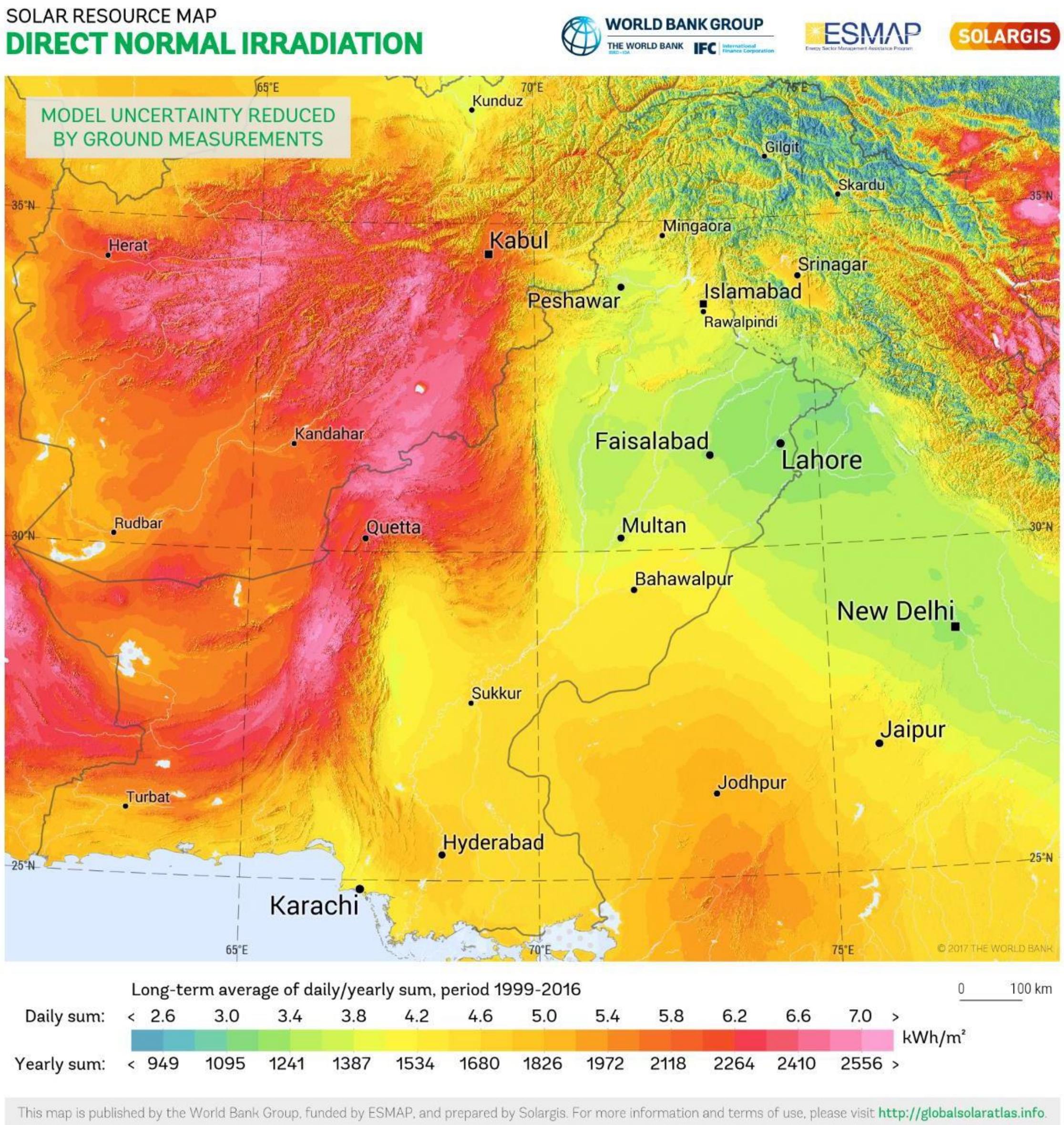

Figure 1-8. Solar irradiance in Pakistan [7]

Another notable renewable energy source in Pakistan is wind power. The coastal areas of Sindh and Balochistan provinces offer favorable wind conditions for harnessing wind energy. Pakistan's total wind power potential is estimated to be around 300 GW [7]. Several wind farms have been established, and more projects are in the pipeline. The government has introduced attractive feed-in tariffs and tax incentives to encourage private sector investment in wind energy projects.

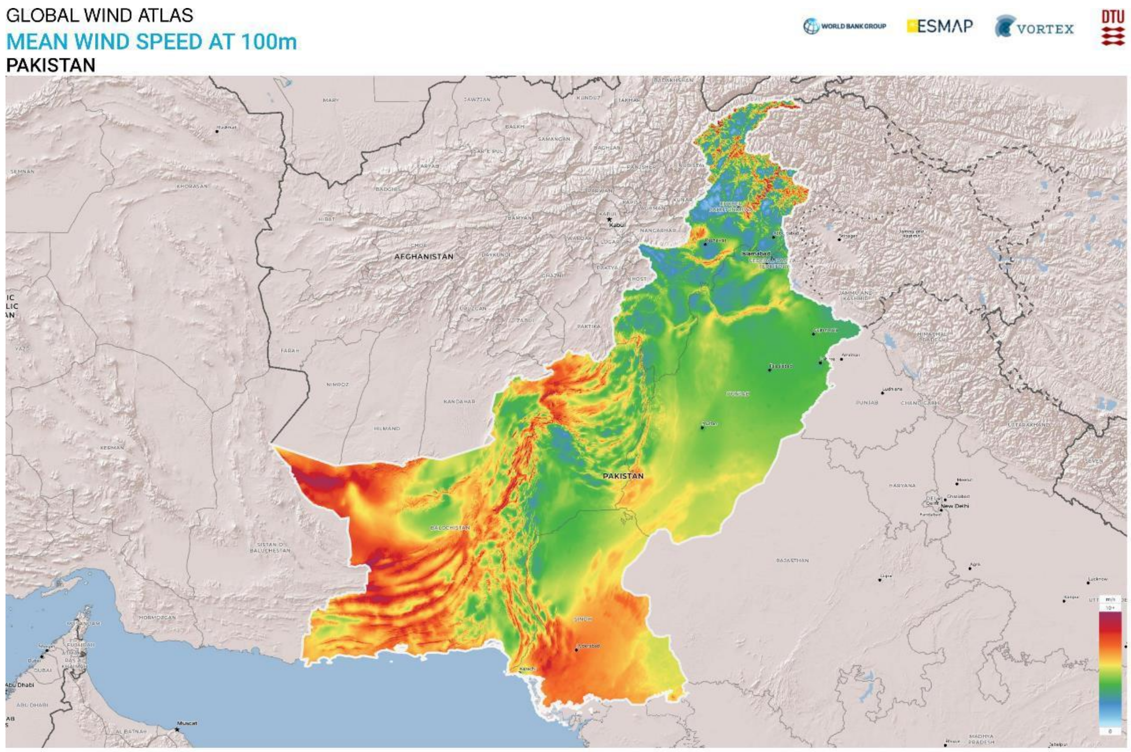

Figure 1-9. Wind Energy Assessment Pakistan [7]

Hydropower is another significant renewable energy resource in Pakistan. The country is endowed with rivers and mountainous regions, making it well-suited for the development of hydropower projects. The Indus River system alone has the potential to generate around 65,000 MW of electricity [7]. Several large-scale hydropower projects, such as the Dasu and Diamer-Bhasha dams, are under construction. These projects aim to increase Pakistan's hydropower capacity and reduce its reliance on fossil fuel-based electricity generation.

Despite Pakistan's substantial renewable energy potential, there are challenges to overcome. These include financing constraints, policy implementation gaps, and the need for improved grid infrastructure to accommodate intermittent renewable energy sources. However, the government, in collaboration with international organizations, is working on addressing these challenges and creating a conducive environment for renewable energy development [7]. The transition to renewable energy in Pakistan offers numerous benefits. It reduces greenhouse gas emissions, improves energy security, creates employment opportunities, and stimulates economic growth [7]. Moreover, renewable energy projects in remote and off-grid areas can provide electricity to communities that are currently underserved by the conventional grid.

One promising alternative to fossil fuels is biogas, which is produced through the anaerobic digestion of organic matter, such as agricultural waste, food waste, and sewage. Biogas can be used as a renewable source of energy for heating and electricity generation, and it has the potential to significantly reduce dependence on conventional fuels.

1.4 Biogas Potential of Pakistan

Pakistan has a significant potential to produce biogas from its biomass resources. The country generates a large amount of agricultural biomass each year, along with dung from millions of animals and droppings from millions of birds in the poultry sector. Biogas is a clean and renewable source of energy that can be used for various purposes, including cooking, heating, and electricity generation.

Pakistan's electricity potential from biogas is estimated to be 32,000 MW [7]. The use of biogas can help to reduce the country's dependence on fossil fuels and improve energy security. Biogas can be produced locally, using locally available biomass resources, which can help to create jobs and support rural development [9]. The use of biogas can also help to reduce the environmental impact of agriculture (waste-wise), by providing a way to manage agricultural waste and reduce greenhouse gas emissions.

To realize the full potential of biogas in Pakistan, there is a need for policy and investment support. The government can provide incentives for the development of biogas projects, such as tax credits, subsidies, and feed-in tariffs [9]. The private sector can also play a role in developing bio-gas projects, by investing in the construction and operation of bio-gas plants.

Pakistan has a significant opportunity to develop a thriving biogas sector that can contribute to the country's energy security and sustainable development [9]. The production of biogas from biomass can help to reduce greenhouse gas emissions and mitigate climate change, while also providing a source of renewable energy. Biogas can be used for various purposes, including cooking, heating, and electricity generation.

1.5 Rural Needs

The current economic crisis in Pakistan has led to an increase in energy costs, making it difficult for many households, particularly those in rural areas, to meet their energy needs.

One of the main effects of the energy crisis on farm households is the impact on cereal crop yields. Major crops such as wheat, rice, and maize have been affected, leading to lower yields and reduced income for farmers. This is because the lack of electricity supply makes it difficult for farmers to irrigate their land on time, which results in planting delays and adversely affects farm productivity. In addition, the lack of electricity supply also makes it difficult for farmers to store their crops properly, which can lead to spoilage and further losses [10].

The impact of the energy crisis on cereal crop yields has also harmed food security in Pakistan. The country is heavily dependent on cereal crops for its food supply, and the lower yields due to the energy crisis have led to higher food prices and reduced access to food for many households [10].

The energy crisis has also had a significant impact on the overall economy of Pakistan. The country's ailing electricity sector is believed to have resulted in a 2% decline in the GDP growth rate per year for the past several years. This has further exacerbated the poverty levels in rural areas, as many farm households are unable to access basic services such as healthcare and education due to the lack of resources [10]

In addition, the impact of the energy crisis on farm households is further compounded by the fact that a large percentage of them do not have the technology to cope with frequent load shedding. This worsens the impacts of the energy crisis and makes it even more difficult for farmers to maintain their livelihoods [10].

To address the energy crisis in Pakistan, policymakers need to find sustainable solutions to ensure that farm households have access to reliable electricity supply. This could include investing in renewable energy sources such as solar and wind power, improving the efficiency of the electricity sector, and providing support to farmers to help them cope with the impacts of the energy crisis. Biogas production has the potential to provide a sustainable and affordable source of energy for these households (albeit at a smaller level).

According to a study by the Alternative Energy Development Board, a small Biogas Digester with a capacity of 6 cubic meters can provide enough gas for cooking and lighting for a family of six for up to six hours per day. This can result in significant cost savings, as the cost of biogas is much lower than other traditional fuels, such as liquefied petroleum gas (LPG) and kerosene.

The cost of biogas production is also significantly lower than other renewable energy sources, such as solar and wind power. According to a study by the Pakistan Council of Renewable Energy Technologies, the cost of producing biogas from animal waste is around Rs. 3.5 per cubic meter, compared to Rs. 12.5 per cubic meter for LPG and Rs. 20 per cubic meter for kerosene.

Despite the cost savings and potential benefits, the biogas sector in Pakistan remains underdeveloped, particularly in small rural households. The main barriers to the development of the biogas sector in these areas include a lack of awareness and knowledge about technology, limited access to financing, and a lack of supportive policies and regulatory frameworks.

To address these barriers, the government of Pakistan has launched several initiatives to promote the development of the biogas sector in rural areas. The Alternative Energy Development Board has launched a biogas program, which provides subsidies and technical support for the installation of Biogas Digesters in rural areas. The government has also introduced policies and regulatory frameworks to promote renewable energy, including biogas, such as the Alternative and Renewable Energy Policy 2019.

In short, biogas production has the potential to provide a sustainable and affordable source of energy for small rural households in Pakistan, reducing their dependence on non-renewable energy sources and helping to alleviate energy poverty. The cost savings of biogas production compared to other traditional fuels make it an attractive option for households facing economic challenges.

Biogas production in Pakistan can be accomplished through various types of anaerobic digesters, each offering distinct parameters and product yields. When considering the specific context of Pakistan, it is crucial to select a digester that is cost-effective and provides a favorable biogas yield. In this regard, the Low-Cost Tubular Biogas Digester emerges as an optimal choice.

1.6 Problem Statement

The import and local production of biogas digesters in Pakistan have surged, but a significant performance gap exists between advertised claims and actual field results. This gap highlights the need for indigenous publications to address crucial aspects of biogas digester technology.

Firstly, there's a need for a comprehensive guide to help designers create biogas digesters that deliver on their theoretical promises. This publication would draw on practical experiences and research to optimize performance.

Additionally, an indigenous publication should focus on designing container boxes tailored to biogas digester requirements, providing practical recommendations for materials, insulation, and maintenance.

Moreover, addressing energy poverty in lower-income and rural areas is vital. An indigenous publication should guide the development of cost-effective and efficient biogas digesters suitable for small-scale installations.

Lastly, a shift towards realistic data-driven design is essential, considering local conditions and challenges, to enhance biogas digester performance and reliability in the Pakistani context.

1.7 Research Objectives

The research objectives for this research are as follows:

1.7.1 Design a Tubular Biogas Digester:

a. Create a design for a tubular biogas digester that can meet the daily energy needs of small households.
b. Optimize the digester's dimensions and specifications to maximize biogas production and efficiency.

1.7.2 Design of a Compact Container Box using SolidWorks:

a. Develop a compact container box design that can effectively house the tubular biogas digester.
b. Consider factors such as insulation, ventilation, and accessibility for maintenance and repair.
c. Use SolidWorks for simulation and analysis of parameters.

1.7.3 Increase Feasibility for Incorporation in Rural Environment:

a. Incorporate portability and ease of installation as key considerations throughout the design process.
b. Develop design features that facilitate easy transportation, assembly, and disassembly of the biogas digester and container box.

1.7.4 Incorporate Possibility of Indigenous Production:

a. Explore and recommend materials that are cost-effective and readily available in Pakistan for constructing the biogas digester and container box.
b. Evaluate the suitability and durability of different materials in the local context.

1.7.5 Techno-Economical Feasibility Analysis

a. Calculate the production cost of the designed biogas digester and container box.
b. Conduct a comparative analysis with existing market alternatives to assess the cost-effectiveness of the proposed design.

By addressing these research objectives, the thesis aims to contribute to the development of a practical and cost-effective solution for small household biogas production in Pakistan.

1.8 Novelty Statement

This research work explores the complex issues surrounding Pakistan's energy crisis, with a particular focus on its impact on small households. To address this crisis, the Design of an Indigenous Small Scale Low-Cost Tubular Biogas Digester with a Portable Container Box has been proposed. This solution involves designing the tubular biogas digester. It is then housed inside a container box, which has been carefully designed to prioritize portability, protection, and ease of installation.

In Pakistan, the availability of tubular biogas digesters is limited, and the existing options are either designed for large capacities or are not suitable for small rural households. The Tubular Biogas Digester and Container Box discussed in this study aim to overcome these limitations. The Tubular Biogas Digester is compact yet fully capable of meeting the energy needs of a small household, distinguishing it from the larger models found in the market. The Container Box, specifically designed to be installed in the ground, such as in a trench, allows for convenient placement near the small household vicinity. This contrasts with the market-available tubular biogas digesters that are positioned above the ground, which not only diminish the aesthetic appeal of the area but also consume excessive space.

The tubular biogas digester and container box are designed to be compact, suitable for supporting small rural households, and have a minimal impact on the overall aesthetics of the surroundings while offering ample space compared to other available options in the market.

The initial design of the tubular biogas digester model, proposed by other authors, approached the problem from an idealistic standpoint, neglecting important factors such as control volume variations and shape differences. As a result, the simulation results significantly diverged from real-life experimentation outcomes. To bridge this gap, a meticulous numerical iteration method has been employed to derive precise parameters for the tubular biogas digester's design.

Once the numerical iteration process was completed, the refined parameters were utilized in the design of the container box model. This container box underwent rigorous analysis to validate its feasibility and effectiveness in fulfilling its intended purpose. The selection of suitable materials for the container box was done with careful consideration given to factors such as durability, strength, and cost-effectiveness. Similarly, the joints used in the assembly of the container box were thoughtfully chosen to facilitate easy assembly, disassembly, and portability, allowing for efficient transportation and relocation of the tubular biogas digester.

By integrating the refined parameters derived from the numerical iteration process, the compatibility between the container box model and the biogas digester was meticulously evaluated. This comprehensive analysis confirmed that the container box provides a secure and efficient housing solution for the digester while also meeting the requirements of easy assembly, disassembly, protection, and portability.

Summary

Fossil fuels, including coal, oil, and natural gas, are widely used for energy production but have negative environmental impacts, such as contributing to climate change and air pollution. Despite these disadvantages, the use of fossil fuels is likely to continue, especially in developing countries. However, there is growing interest in renewable energy sources like solar, wind, and hydropower to reduce environmental impacts. Pakistan faces an energy crisis due to a mismatch between energy demand and supply, heavy reliance on fossil fuels, inadequate planning, and underutilization of nuclear energy. The country has significant potential for renewable energy, including solar, wind, hydropower, and biogas. Biogas production can help address rural energy needs, reduce dependence on non-renewable sources, and alleviate energy poverty. However, the biogas sector in Pakistan faces barriers such as a lack of awareness, financing, and supportive policies. The development of indigenous publications and suitable container boxes for biogas digesters is crucial for optimizing their performance.

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Chapter 2: Literature Review

2.1 Biogas

Biogas is a versatile and environmentally friendly energy source that is generated through the anaerobic digestion of organic matter by bacteria. This naturally occurring gas primarily consists of methane, carbon dioxide, and trace amounts of nitrogen, hydrogen, and carbon monoxide. Biogas stands apart from natural gas, which is a fossil fuel formed over geological time, as it is produced biologically and is considered a renewable energy source [1].

The formation of biogas occurs in various natural settings, such as compost heaps, where organic materials decompose under anaerobic conditions [1]. It can also be found as swamp gas, produced by the decomposition of organic matter in wetlands. In addition, biogas is a byproduct of enteric fermentation in the digestive systems of animals, particularly in the rumen of cattle and other ruminants. This natural production of biogas contributes to the methane emissions associated with livestock farming.

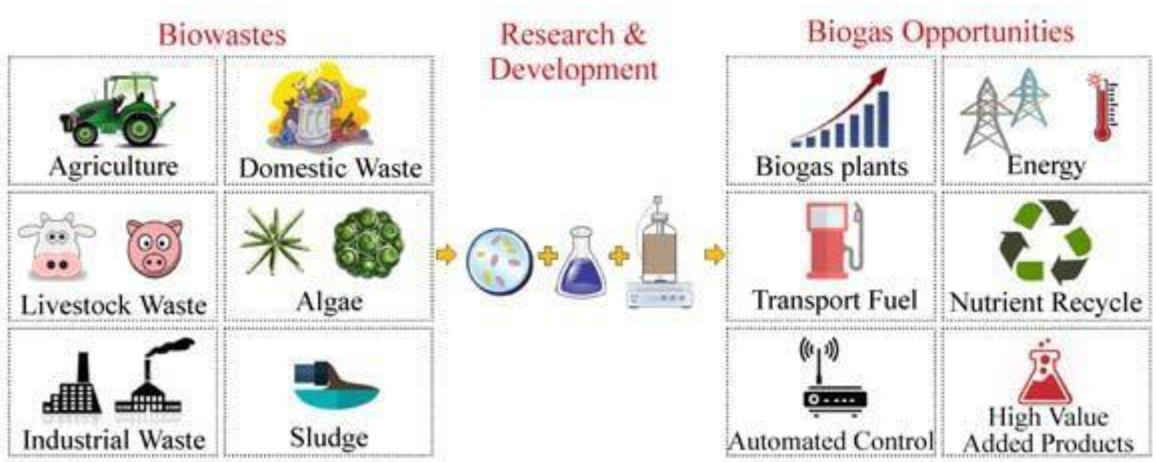

Figure 2-1. Overview of Biogas Opportunities and Production [1]

However, biogas can also be intentionally produced in controlled environments known as anaerobic digesters. These digesters are designed to optimize the decomposition process and capture the biogas generated from the breakdown of organic waste [1][2]. The organic waste used in anaerobic digesters can come from various sources, including agricultural residues, food waste, sewage sludge, and energy crops [1][2][3].

The anaerobic digestion process involves several stages. Initially, the organic waste is collected and introduced into the digester, either as a liquid or in the form of a slurry mixed with water. The digester provides an oxygen-free environment that facilitates the growth and activity of anaerobic bacteria responsible for breaking down organic matter. As the bacteria metabolize organic waste, they produce biogas as a byproduct. This biogas consists mainly of methane, which is the primary component responsible for its energy content [1][3][4].

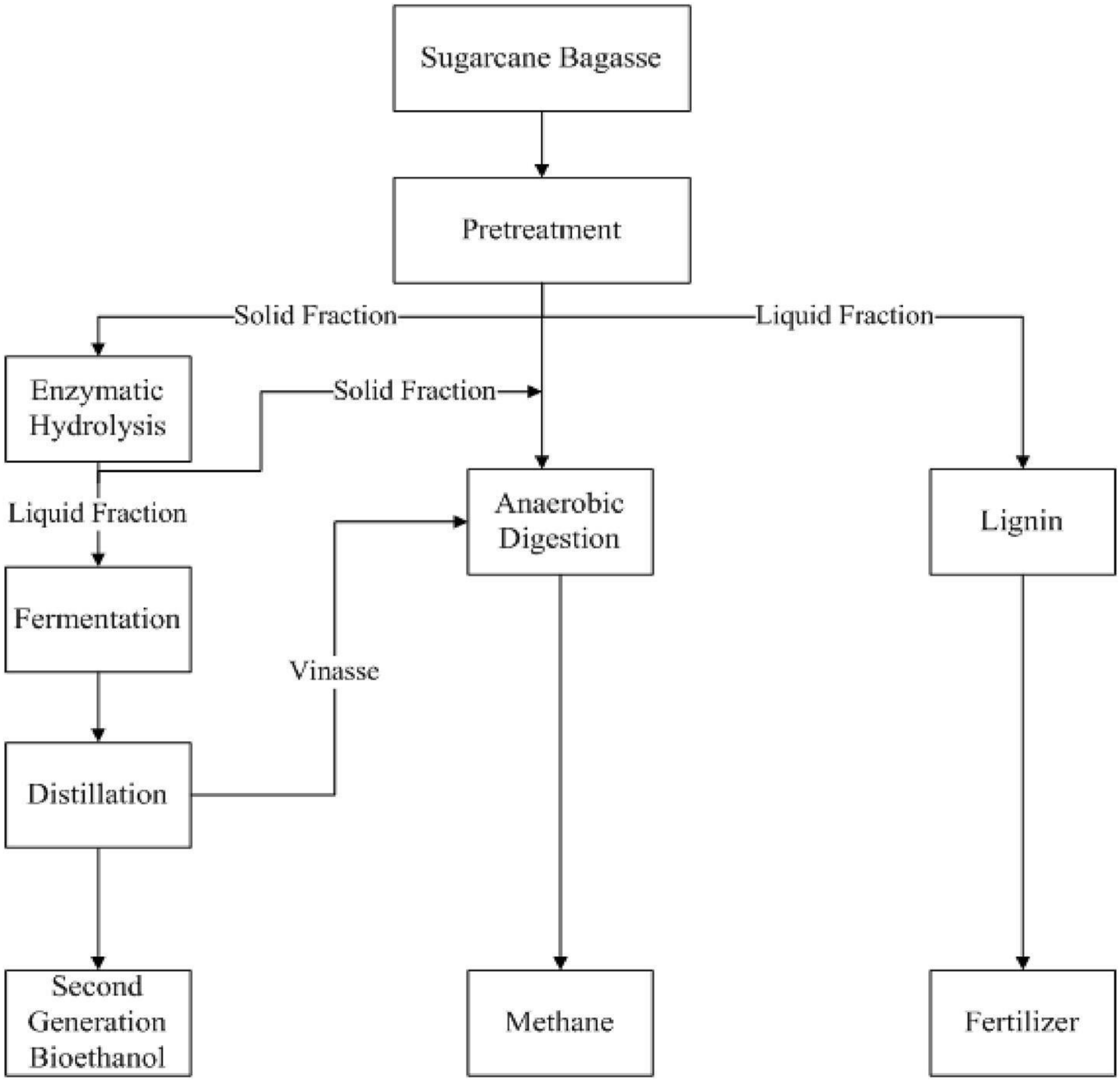

Figure 2-2. Biogas production using biomass substrate [2]

Anaerobic digesters are typically composed of different components, including a feedstock source holder, a digestion tank, a biogas recovery unit, and heat exchangers [5]. The feedstock source holder serves as the initial storage for the organic waste before it is introduced into the digester. The digestion tank is where the anaerobic decomposition process takes place, and the biogas recovery unit collects and stores the produced biogas.

Heat exchangers are used to maintain the optimal temperature for bacterial activity within the digester, enhancing the efficiency of biogas production.

The utilization of biogas offers numerous environmental benefits. One significant advantage is the reduction of greenhouse gas emissions. By capturing and utilizing biogas as an energy source, the release of methane, a potent greenhouse gas, is significantly reduced compared to when organic waste undergoes natural decomposition in landfills or other uncontrolled settings [2]. Methane has a considerably higher global warming potential than carbon dioxide, so by replacing methane emissions with carbon dioxide through the efficient combustion of biogas, there is a net reduction in greenhouse gas impact.

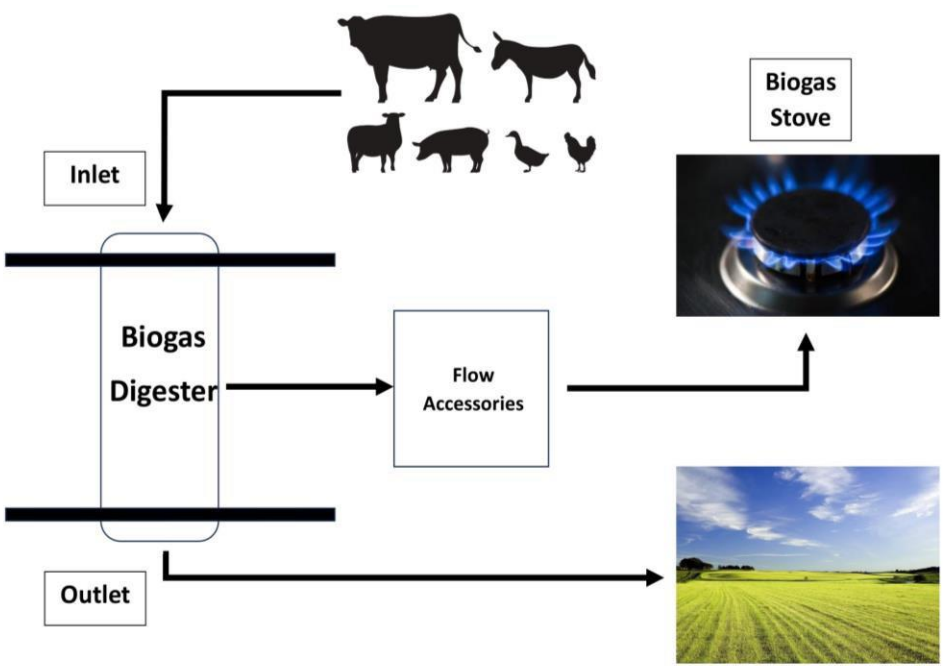

Figure 2-3. A typical small-scale biodigester [5]

Biogas also contributes to sustainable waste management by providing an effective solution for the treatment and utilization of organic waste [1][4]. Instead of allowing organic waste to accumulate in landfills, where it can release harmful greenhouse gases and contribute to environmental pollution, anaerobic digestion enables the transformation of this waste into a valuable energy resource [2]. Moreover, the digestion process reduces the odors, insects, and pathogens associated with traditional manure stockpiles, making it a more environmentally friendly option for agricultural waste management.

The application of biogas is diverse and ranges from household-scale to large-scale energy production. Small-scale anaerobic digesters sometimes referred to as household digesters, can be used in rural areas to provide cooking fuel and lighting for individual homes [2][3]. These digesters typically have a smaller capacity and are designed to meet the energy needs of a single household [5].

To ensure the optimal utilization of biogas, proper treatment and purification processes are essential. Scrubbing techniques can remove impurities such as hydrogen sulfide and volatile siloxanes, ensuring the biogas meets quality standards for various applications, including vehicle fuel or injection into gas pipelines [3].

2.2 Biogas Production Process

The production of biogas occurs via anaerobic digestion. Generally, it begins with the collection of organic matter, such as agricultural waste, food waste, and sewage. The organic matter is mixed with water and placed in an anaerobic digester, which is a sealed container that provides an oxygen-free environment for the organic matter to break down through the action of bacteria. As the organic matter breaks down, biogas is produced, which can be captured and used as fuel.

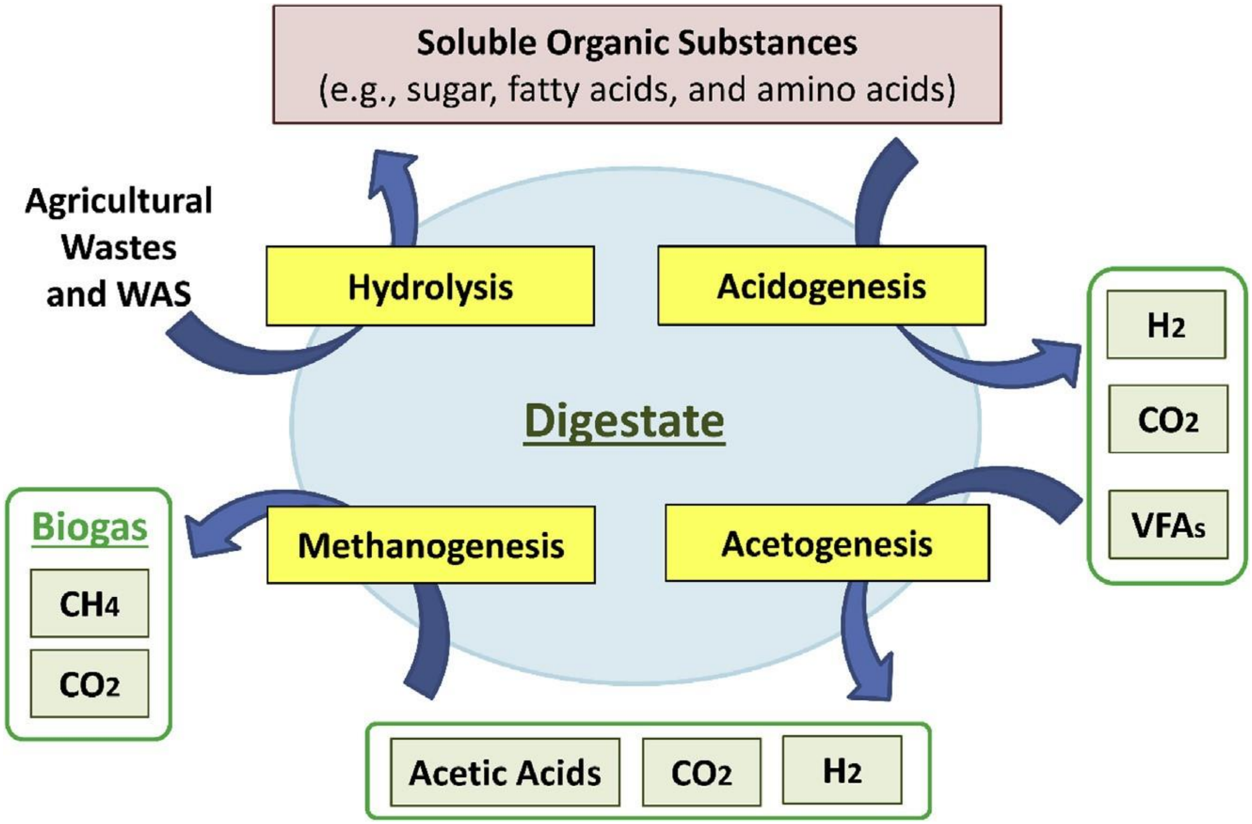

Figure 2-4. Complete biogas production/anaerobic digestion process [6]

The process of biogas production can be divided into four stages [3][6]:

2.2.1 Hydrolysis

In anaerobic digestion, the majority of biomass consists of large organic polymers. However, for the bacteria present in anaerobic digesters to effectively access the energy potential of these materials, the complex chains of these polymers must be broken down into smaller constituent parts. This process of breaking down the complex chains and dissolving the resulting smaller molecules into a solution is known as hydrolysis [7]. Hydrolysis serves as the necessary initial step in the anaerobic digestion process, as it enables the conversion of high-molecular-weight polymeric components into simpler forms, such as sugars, amino acids, and fatty acids [8].

Hydrolysis plays a vital role in anaerobic digestion by facilitating the breakdown of complex organic molecules into more accessible substrates [7]. These smaller molecules, such as sugars, amino acids, and fatty acids, are readily available for utilization by other bacteria involved in subsequent stages of anaerobic digestion. This breakdown process ensures that the energy locked within the complex organic matter is made available for further microbial metabolism [7].

Additionally, the products of hydrolysis, including acetate and hydrogen, can be directly utilized by methanogenic microorganisms. However, certain molecules, such as volatile fatty acids (VFAs) with chain lengths longer than that of acetate, require further catabolism to be transformed into compounds that can be readily utilized by methanogens [7]. This step allows for the efficient conversion of complex organic compounds into methane, a key component of biogas.

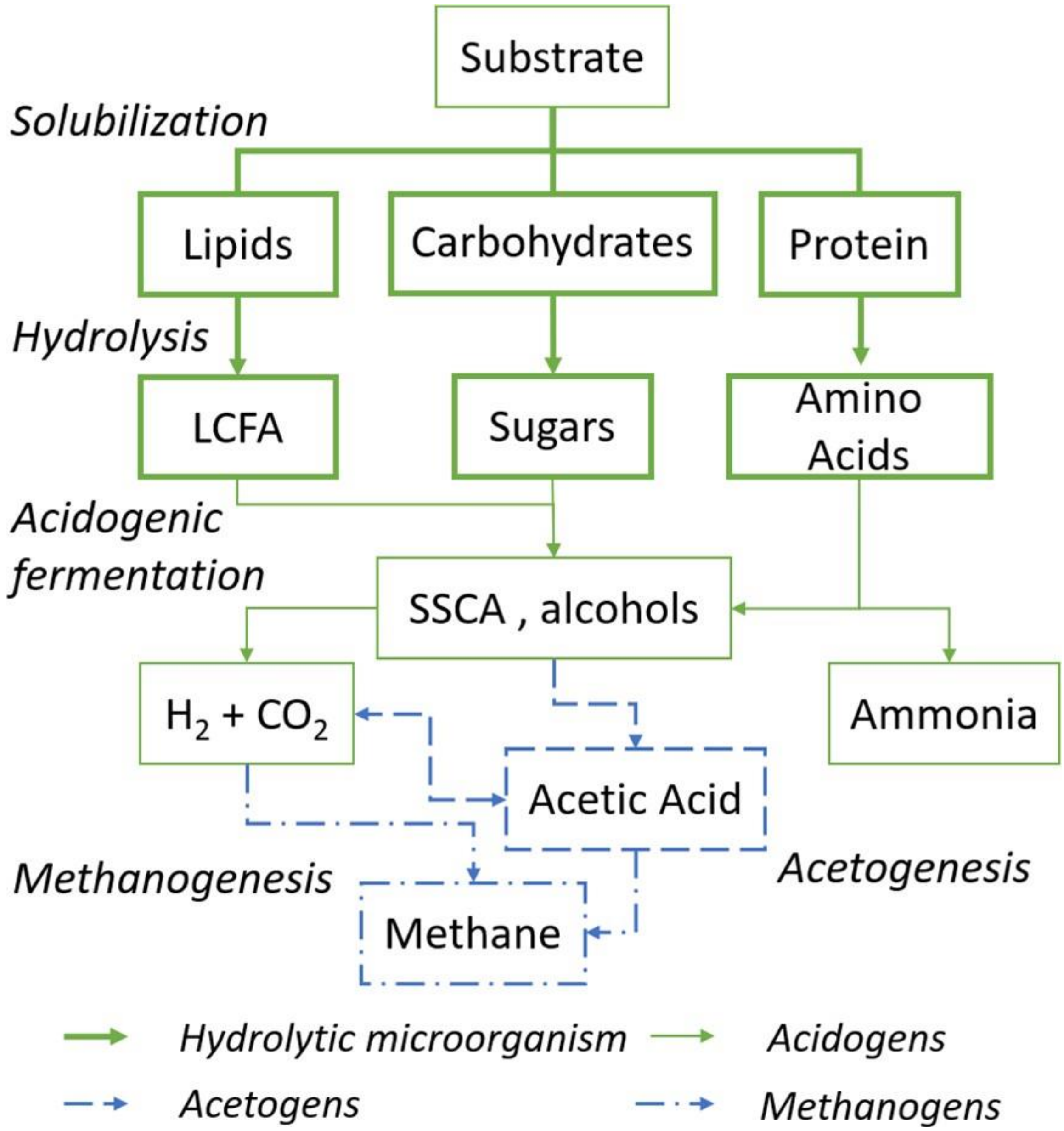

Figure 2-5. Product breakdown due to different stages of the anaerobic digestion process [7]

By initiating the breakdown of complex organic matter, hydrolysis sets the stage for subsequent stages of anaerobic digestion, enabling the conversion of these simpler molecules into biogas components. The efficient and thorough hydrolysis of high-molecular-weight polymers is crucial for maximizing the biogas yield and overall efficiency of the anaerobic digestion process.

2.2.2 Acidogenesis

During acidogenesis, a crucial biological process, acidogenic (fermentative) bacteria undertake the breakdown of the remaining components with remarkable precision. This breakdown leads to the creation of various substances, including volatile fatty acids (VFAs), ammonia, carbon dioxide, and hydrogen sulfide, among other byproducts. These acidogenic bacteria, through their enzymatic activities, initiate the fermentation of organic matter, resulting in the generation of VFAs [8].

As the breakdown progresses, the acidogenic bacteria metabolize complex organic compounds, such as carbohydrates, proteins, and lipids, present in the initial substrate. This metabolic activity leads to the release of VFAs, which serve as vital intermediates in subsequent biological processes. VFAs encompass a range of organic acids, including acetic acid, propionic acid, and butyric acid, each contributing to the overall complexity of the breakdown products [8].

Furthermore, the acidogenesis process also produces ammonia, carbon dioxide, and hydrogen sulfide. Ammonia (NH3) is a byproduct resulting from the deamination of amino acids found in proteins, while carbon dioxide (CO2) arises from the metabolism of various carbon sources. Additionally, hydrogen sulfide (H2S) is formed due to the breakdown of sulfur-containing compounds present in the substrate.

Analogous to the natural souring of milk, acidogenesis occurs through a series of microbial transformations. The acidogenic bacteria, through their metabolic activities, create an acidic environment that facilitates the breakdown of organic matter. This process bears similarity to the fermentation of lactose by lactic acid bacteria, leading to the souring of milk.

2.2.3 Acetogenesis

The third stage of anaerobic digestion, known as acetogenesis, plays a crucial role in the overall process. At this stage, the organic compounds produced during the preceding acidogenesis phase undergo further decomposition and conversion by specialized microorganisms called acetogens [8].

Acetogens are adept at metabolizing the intermediate products generated earlier and carrying out a complex set of biochemical reactions. They efficiently break down these compounds into a variety of end products, with acetic acid being the primary outcome. Additionally, carbon dioxide and hydrogen gas are also released during this process [7][8].

The intricate mechanisms employed by acetogens involve intricate enzymatic pathways that catalyze the conversion of organic molecules into acetic acid. These microorganisms possess unique metabolic capabilities that allow them to carry out these conversions under anaerobic conditions, without the presence of oxygen [8].

As the acetogens break down the organic matter, they extract energy from the chemical bonds within the molecules. This energy is utilized by microorganisms for their growth and maintenance, enabling them to thrive in the anaerobic environment.

The production of acetic acid, along with the release of carbon dioxide and hydrogen, serves as an important link in the overall anaerobic digestion process. These end products, in turn, provide the necessary substrates for subsequent stages of the process, such as methanogenesis, where methane-producing microorganisms utilize them to generate methane gas [7].

2.2.4 Methanogenesis

The terminal stage of anaerobic digestion, known as methanogenesis, is a complex biological process crucial to produce biogas. Methanogens, specialized microorganisms, play a vital role in this phase by utilizing the intermediate products generated in the preceding stages of anaerobic digestion [8].

During methanogenesis, methanogens convert these intermediate products, such as volatile fatty acids, alcohols, and other organic compounds, into three main components: methane (CH4), carbon dioxide (CO2), and water (H2O) [7][8]. These compounds together constitute the bulk of the biogas emitted from the anaerobic digestion system.

However, methanogenesis is a sensitive process influenced by various environmental factors, with pH being a crucial parameter. Optimal methanogenesis occurs within a relatively narrow pH range, typically between 6.5 and 8 [9]. Deviations from this range, either towards highly acidic or highly alkaline conditions, can significantly affect the efficiency of the process. Extreme pH values can inhibit the activity of methanogens, leading to reduced biogas production [3][9].

Furthermore, the final byproduct of anaerobic digestion, known as digestate, consists of two main components. Firstly, it includes the undigested materials that microbes within the system were unable to break down and utilize. These materials can comprise complex compounds, such as lignocellulosic biomass, resistant to degradation under anaerobic conditions. Secondly, the digestate also contains any dead bacterial remains from the anaerobic microbial consortium [8].

Recent trends and advancements in the production of biogas have focused on improving the efficiency and scalability of the process. One key development has been the use of high-solid digesters, which can process a wider range of organic materials and produce higher yields of biogas. Another development has been the use of co-digestion, which involves mixing multiple types of organic materials in the digester to increase the diversity and availability of feedstock [6][9].

2.3 Biogas Digesters

Biogas digesters, also referred to as anaerobic digesters, are sophisticated engineered systems designed to facilitate the process of anaerobic digestion for the effective breakdown of organic materials in the absence of oxygen. This natural biological phenomenon involves the decomposition of organic matter by a diverse community of microorganisms, primarily anaerobic bacteria [3].

Biogas digesters serve as a purpose-built infrastructure that optimizes and controls the anaerobic digestion process, maximizing its efficiency and enhancing biogas production. Comprised of various essential components, including a digester tank or vessel, an inlet for introducing organic materials (feedstock), an outlet for the digested material (digestate), and a biogas collection system, these digesters ensure the efficient conversion of organic waste into valuable resources [3][5].

The versatility of biogas digesters lies in their ability to accommodate a wide range of organic materials as feedstock. This includes agricultural waste, food waste, sewage sludge, and dedicated energy crops, enabling the effective management and utilization of diverse organic waste streams [3]. By diverting these materials from traditional disposal methods, such as landfilling or incineration, biogas digesters contribute to waste reduction and promote environmental sustainability [5].

The process within biogas digesters can be divided into several stages. Initially, the feedstock is introduced into the digester tank, which is sealed to create an oxygen-free environment. This controlled setting encourages the proliferation of specific anaerobic microorganisms that thrive in the absence of oxygen [3].

Within the digester, a cooperative microbial community, including acidogens, acetogens, and methanogens, collaborates to break down complex organic compounds present in the feedstock [3][8]. Acidogens play a crucial role by converting complex molecules into simpler compounds, such as volatile fatty acids and hydrogen [8]. Subsequently, acetogens further metabolize these intermediates, producing acetic acid and other compounds [8].

Finally, methanogens utilize the resulting compounds and convert them into biogas, which primarily consists of methane (CH4) and carbon dioxide (CO2) [9]. The biogas rises to the top of the digester and is collected through a biogas collection system. The remaining digestate, enriched with nutrients, can be utilized as a high-quality fertilizer, contributing to sustainable agriculture and closing the nutrient cycle [3][5].

The deployment of biogas digesters brings forth numerous environmental and socio-economic advantages. By effectively managing organic waste, these digesters contribute to waste reduction, mitigating its adverse environmental impact and addressing odor concerns. Additionally, by capturing and utilizing biogas, they help mitigate greenhouse gas emissions, as methane, the primary component of biogas, possesses a significantly higher global warming potential than carbon dioxide. Moreover, biogas digesters promote sustainable agriculture, rural development, and energy security by providing decentralized and renewable energy solutions [5][6][8].

2.4 Types of Biogas Digesters

Biogas digesters offer a range of subcategories based on their intended purpose and scale of utilization. This thesis focuses primarily on small-scale biodigesters, which play a crucial role in decentralized energy generation and waste management. Small-scale biogas digesters are typically designed to meet the energy needs of individual households, small communities, or small-scale farming operations [3][5]. They are often referred to as household biogas digesters. These digesters are compact in size and can be installed in residential properties, farms, or rural areas where there is limited availability of grid electricity or access to alternative energy sources [5]. They utilize organic waste materials, such as kitchen waste, animal manure, or crop residues, to produce biogas for cooking, heating, and lighting purposes. In addition to biogas production, small-scale digesters also generate nutrient-rich organic fertilizer as a byproduct, which can be used to enhance soil fertility in agriculture [3][5]. The types of Small-Scale Biogas Digesters are as follows:

2.4.1 Fixed Dome Biogas Digester

In the 1930s, Chinese innovators made significant strides in the field of biogas technology with the development and construction of the fixed dome biogas system. This remarkable system brought about a paradigm shift in biogas production and storage methods. It comprises a meticulously designed underground brick masonry compartment known as the fermentation chamber, which serves as the heart of the system. Atop the fermentation chamber, a dome structure is incorporated, specifically engineered for efficient gas storage.

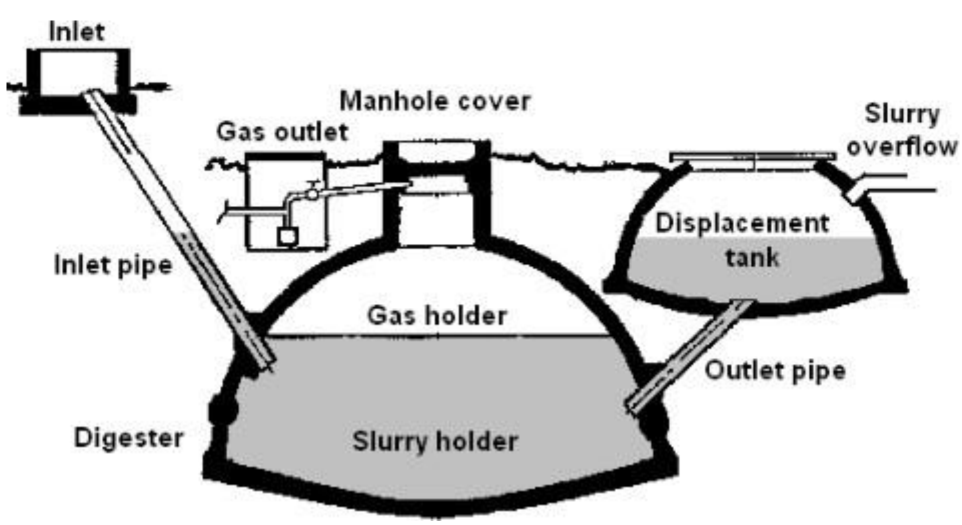

Figure 2-6. Fixed-Dome Biogas Digester [3]

The fixed dome Biogas Digester operates through a well-defined process. The enclosed digester, located within the fermentation chamber, features a gas space that remains stationary and cannot be moved. The upper part of the digester is dedicated to the storage of the generated biogas. As the biogas production commences, the slurry—a mixture of organic waste and water—undergoes fermentation inside the digester. The digestion process releases biogas, causing the slurry level to rise. In response, the excess slurry is displaced into a compensating tank to maintain optimal gas storage capacity within the digester [10].

One critical aspect to consider in fixed-dome Biogas Digesters is the gas pressure within the system. The volume of gas stored directly influences the gas pressure, and therefore it is crucial to carefully manage this parameter [3]. To ensure efficient gas utilization, it is recommended that the volume of the digester does not exceed 20 m^3. If the gas holder contains only a small amount of gas, the gas pressure remains low, potentially limiting certain applications. However, when constant gas pressure is required for specific purposes, such as for engines, additional components are introduced. These may include a gas pressure regulator or a floating gas holder [10]. Engines typically consume a significant amount of gas, necessitating the integration of larger gas holders to meet the demand. Without a floating gas holder, the gas pressure could exceed the desired levels, potentially leading to operational issues.

2.4.2 Floating Drum Biogas Digester (FDB)

The Floating Drum Biogas (FDB) system is a highly advanced and cost-effective biogas digester specifically engineered to address the environmental impact caused by animal waste. By utilizing the principles of anaerobic digestion, this cutting-edge technology facilitates the conversion of various organic materials, including plant waste and animal byproducts, into valuable energy sources such as electricity and cooking fuel.

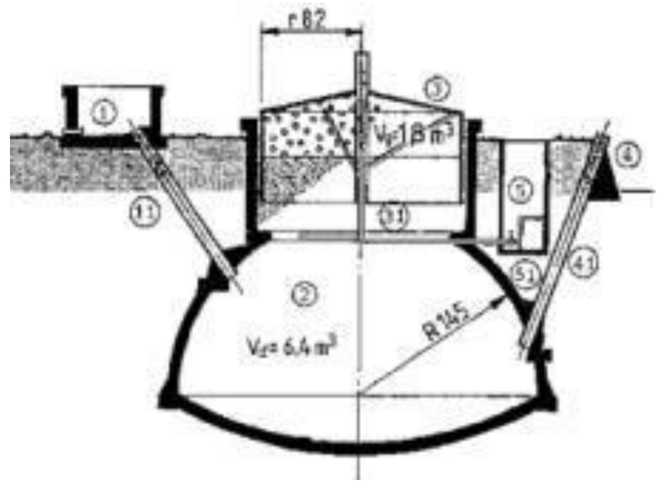

Figure 2-7. Floating Drum Biogas Digester [3]

The FDB distinguishes itself through its innovative floating design, which serves multiple critical functions. Firstly, it ensures that the digester remains unaffected by flooding, enabling uninterrupted operation even in regions prone to water accumulation or high-water tables [3]. This design feature also provides an added advantage by creating an enclosed environment that effectively retains the heat generated during the digestion process, optimizing the efficiency of biogas production [3]. Additionally, the floating system allows for controlled drainage of excess liquid, ensuring the proper balance and consistency of the digester's contents.

Beyond its resilience to flooding, the FDB demonstrates exceptional robustness in earthquake-prone areas [11]. The floating drum's sturdy construction and flexible response to seismic activity make it an ideal choice for regions that experience frequent tremors. This enhanced structural integrity ensures the continued operation and longevity of the system, making it a reliable and durable solution for biogas production in such geologically active zones [11].

The FDB system comprises two primary components: the digester and the moving gasholder [11]. The gas holder is ingeniously designed to either float directly on the fermentation slurry or within a water jacket, depending on the specific configuration. As the anaerobic digestion process progresses, the gas generated from the decomposition of organic matter accumulates within the drum, causing it to rise due to positive pressure.

When the biogas is extracted for utilization, the drum descends accordingly [11]. To maintain stability and prevent any tilting or imbalance, a meticulously designed guide frame is incorporated into the system.

2.4.3 Earth-Pit Biogas Digesters

In regions with stable soil conditions, such as laterite, the use of masonry digesters may not be necessary. Instead, an alternative method can be employed to construct a cost-effective and efficient biogas digester. This approach involves lining the excavation pit with a thin layer of cement, which acts as a protective barrier against seepage. To ensure the structural integrity of the digester, wire mesh is fixed to the pit walls and plastered with cement. Additionally, a reinforced masonry ring is constructed along the edge of the pit, serving the dual purpose of providing stability and acting as an anchorage for the gas holder [12

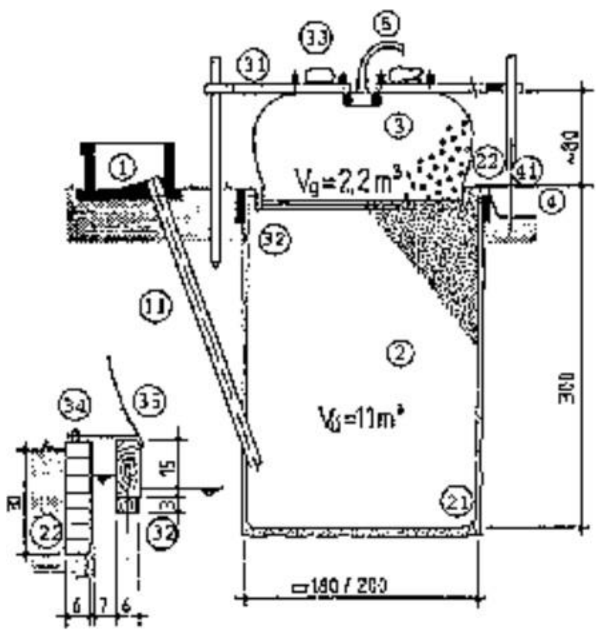

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Figure 2-8. Earth Pit Biogas Digester [12]

The gasholder itself can be made either from metal or plastic sheeting, offering flexibility in material choice. However, when opting for plastic sheeting, it is crucial to attach it to a square wooden frame that extends into the slurry and is securely anchored to counterbalance its buoyancy. To achieve the desired gas pressure within the system, weights are placed on the gas holder, ensuring efficient gas production and storage. Furthermore, to facilitate the removal of excess slurry, an overflow point is incorporated into the peripheral wall, enabling proper drainage [12].

This particular biogas digester design offers several advantages. Firstly, the installation costs are significantly lower compared to floating-drum plants, often amounting to as little as 20% of the expenses associated with alternative systems [12]. This cost-effectiveness opens opportunities for self-help approaches, allowing communities to actively participate in the construction process and promote sustainable energy solutions within their regions.

However, it is important to consider the limitations of this design as well. The earth-pit Biogas Digesters with plastic sheet gas holders have a relatively shorter useful life compared to other systems. Moreover, it is essential to install them only in impermeable soil located above the groundwater table. These factors should be considered when assessing the suitability of this type of digester for a specific location, considering soil characteristics, available resources, and long-term sustainability goals [12]. By carefully evaluating the advantages and disadvantages, communities can make informed decisions regarding the implementation of biogas digesters that best meet their needs and local conditions.

2.4.4 Ferro-Cement Biogas Digesters

Ferrocement Biogas Digesters are a type of biogas digester constructed using a combination of cement mortar and reinforcement materials, typically wire mesh or steel bars. This construction technique involves applying multiple layers of cement mortar mixed with sand onto the reinforcement structure, resulting in a durable and sturdy Biogas Digester [12].

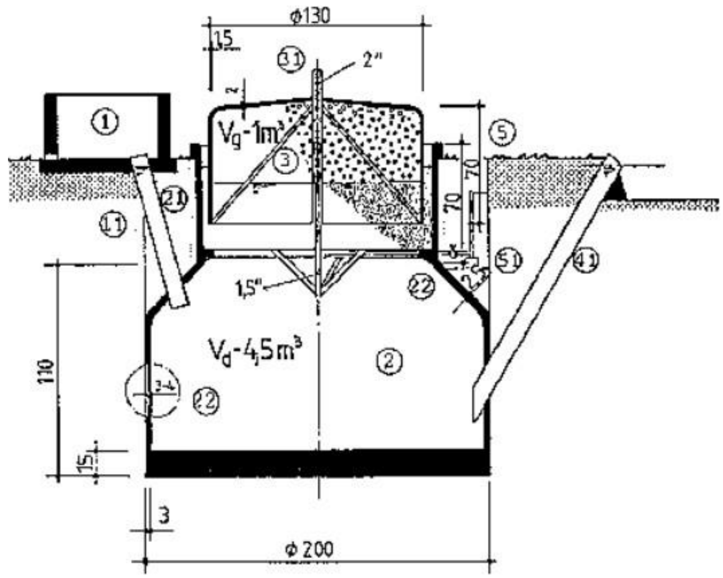

Figure 2-9. Ferrocement Biogas Digester [12]

The process of building a ferrocement Biogas Digester typically begins with excavating a pit of appropriate size and shape. The pit is then lined with a layer of plastic sheeting or a waterproof membrane to prevent seepage. Following this, a network of wire mesh or steel bars is strategically placed within the pit, forming the internal framework of the Biogas Digester [12].

Next, multiple layers of cement mortar, consisting of cement, sand, and water, are applied to the reinforcement structure. The mortar is meticulously spread and compacted to ensure a uniform thickness and a strong bond between the layers. The application of several layers enhances the strength and resilience of the Biogas Digester [12].

The construction of a ferrocement Biogas Digester also involves incorporating inlet and outlet pipes for the feedstock and digested slurry respectively. Gas outlets are installed to allow for the collection and utilization of biogas. A gasholder, typically made of plastic sheeting or an alternative gas storage mechanism, is employed to capture and store the biogas produced during the anaerobic digestion process [12].

Ferrocement Biogas Digesters provide a versatile and durable solution for biogas digestion, with the ability to be constructed as a self-supporting shell or an earth-pit lining.

The vessel is commonly designed in a cylindrical shape, and for smaller plants (volume under 6 m3), prefabrication options are available [12]. Like fixed-dome plants, special sealing measures are required for the ferrocement gasholder, with proven reliability achieved using cemented-on aluminum foil.

Ferrocement Biogas Digesters offer several advantages. The use of cement mortar and reinforcement materials provides excellent structural strength and durability. They can withstand environmental conditions, resist seepage, and have a longer service life compared to some other biogas digester designs. Additionally, ferrocement Biogas Digesters can be built at a lower cost compared to more complex digester systems, making them a cost-effective option for communities with limited resources [12].

While offering advantages, ferrocement Biogas Digesters also present some considerations. The construction process involves a substantial consumption of good-quality cement, which can result in higher costs. Moreover, achieving the necessary workmanship quality standards is crucial to ensure the structural integrity and longevity of the Biogas Digester. Additionally, the use of expensive wire mesh in substantial amounts adds to the overall expenses [12]. It is worth noting that the construction technique of ferrocement Biogas Digesters is still undergoing evaluation and may not have been extensively time-tested in all scenarios. Special sealing measures are also necessary for the gasholder to ensure gas tightness.

Considering these factors, ferrocement Biogas Digesters are recommended only when there is access to specialized ferrocement know-how. This expertise is essential to properly apply the construction technique, ensuring the reliability and effectiveness of the Biogas Digester.

2.4.5 Tubular Biogas Digester

The low-cost tubular biodigester is an affordable, simple, and efficient type of biogas digester that has gained popularity in recent years. It offers a practical solution for households and small-scale farms in developing countries to generate biogas for cooking, lighting, and other energy needs [3][5].

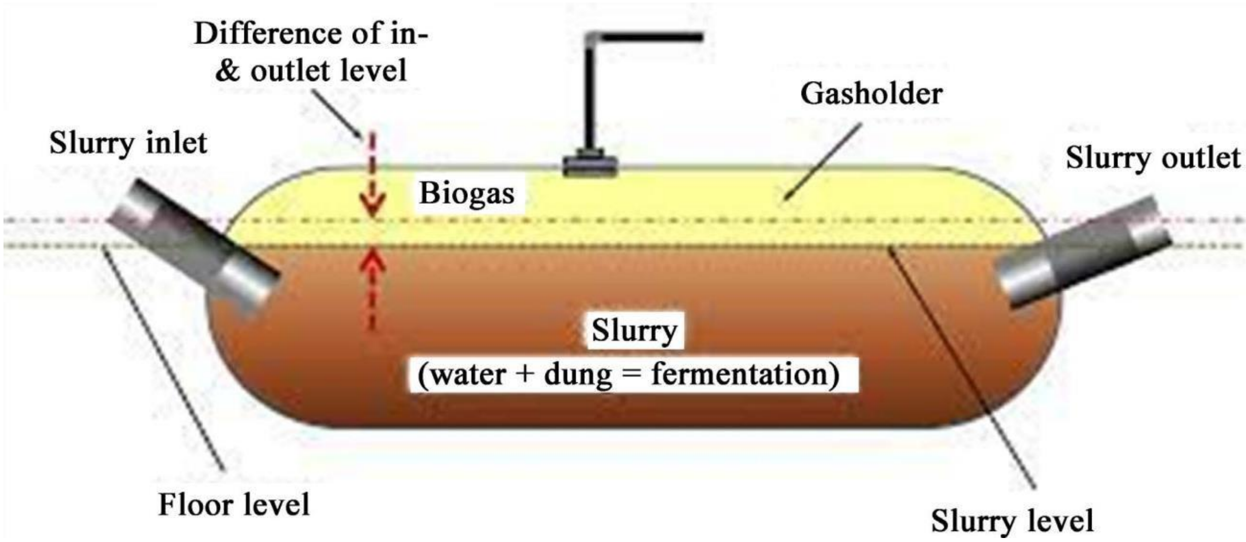

Figure 2-10. Tubular Biogas Digester [13]

The biodigester utilizes a flexible plastic or PVC tube that is buried in a trench lined with sand or concrete. The tube is filled with a mixture of organic waste and water, which undergoes anaerobic digestion. This process breaks down the organic matter, producing biogas and a nutrient-rich slurry [13].

Operating on the principle of anaerobic digestion, the biodigester relies on bacteria to decompose the organic matter in the absence of oxygen. The biogas, consisting primarily of methane and carbon dioxide, is collected at the top of the tube and can be utilized for various energy purposes. The nutrient-rich slurry serves as a valuable fertilizer for crops [3][13].

The low-cost tubular biodigester offers several advantages. Firstly, it is affordable and can be constructed using locally available materials, making it accessible to low-income households and small-scale farmers. The construction cost can range from $150 to $300. Secondly, its tubular shape promotes efficient digestion, enabling quicker biogas and slurry production compared to other digester types. Depending on the feedstock and environmental conditions, it can produce up to 2-3 cubic meters of biogas per day. Additionally, the biodigester requires minimal maintenance and is easily repairable. With proper care, the PVC tubes can last for up to 10 years. Lastly, the biogas produced serves as a sustainable energy source, reducing dependence on non-renewable fuels and contributing to a decrease in greenhouse gas emissions [13].

For this research work, the Tubular Biogas Digester is chosen as the basis for the design. The reasons for that are stated as follows:

When considering the suitability of tubular biogas digesters compared to fixed dome Biogas Digesters, floating drum plants, earth-pit plants, and ferro-cement plants for household use in Pakistan, several detailed reasons highlight the feasibility of tubular digesters. The reasons are as follows:

a. Continuous Feed: Tubular biogas digesters offer the advantage of continuous feed, allowing for a steady and uninterrupted supply of organic waste. This ensures a consistent production of biogas, eliminating the need for batch processing and enabling a continuous source of energy for household needs [14]
b. Enhanced Gas Production: The long and narrow design of tubular digesters creates an optimal environment for efficient digestion, resulting in higher gas production rates compared to other digester types. This improved gas production capability ensures a reliable and substantial supply of biogas for household cooking and lighting [14].
c. Versatile Waste Compatibility: Tubular digesters exhibit versatility in handling various types of organic waste commonly generated in households, including kitchen waste, crop residues, and animal manure. This flexibility allows for effective waste management and harnessing the energy potential of diverse organic materials [14].
d. Compact Design: With their smaller footprint, tubular digesters are well-suited for households in Pakistan, particularly in densely populated areas where space is limited. The compact design enables their installation in small available spaces, making them an ideal choice for urban and peri-urban households [3][14].
e. Lower Construction Costs: Tubular digesters offer the advantage of relatively lower construction costs compared to other biogas digester types.

Their simpler design and the use of readily available materials contribute to reduced expenses, making them more financially accessible for households, especially those with limited resources [3][14]

f. Ease of Installation: Tubular digesters are relatively easy to install, requiring minimal modifications to existing household infrastructure. The simplicity of their design and installation process allows for quick and hassle-free deployment, ensuring a smoother adoption of biogas technology in households [3][14].
g. Lower Maintenance Requirements: Tubular digesters have straightforward structures and operational mechanisms, resulting in lower maintenance requirements and associated costs. This factor is particularly advantageous for households in Pakistan, where access to skilled labor and technical support may be limited [3][14].
h. Reliable Gas Supply: The continuous feed and efficient gas production of tubular digesters ensure a reliable and consistent supply of biogas. This dependable energy source meets household cooking and lighting needs, reducing dependence on other fuel sources and enhancing energy self-sufficiency [14].
i. Adaptability to Various Waste Quantities: Tubular digesters can effectively process both small and large quantities of organic waste, providing flexibility in waste management based on household needs and waste generation rates. This adaptability allows households to maximize the utilization of available waste resources [14].
j. Scalability for Different Household Sizes: Tubular digesters can be scaled to match the energy demands of different household sizes, accommodating both small and large households. This scalability feature enables tailored biogas solutions that align with specific household requirements, optimizing energy production and utilization [14].

2.5 Current Biogas Digester Scenario in Pakistan

Pakistan, like many countries around the world, has experienced both successes and challenges in the implementation of biogas technology. While the country has made notable strides in this field, the widespread adoption of biogas remains a work in progress. Currently, approximately six thousand digesters have been installed, but the potential for Pakistan is much greater, with an estimated capacity for around five million digesters, thanks to its favorable climate conditions and abundant livestock population [15].

One significant milestone in Pakistan's biogas journey was the comprehensive biogas scheme initiated by the Government in 1974. Over the course of more than a decade, from 1974 to 1987, the government commissioned an impressive total of 4,137 biogas units across the country. These units were large-scale plants capable of producing varying amounts of gas each day, ranging from 5 to 15 cubic meters [15].

In addition to government initiatives, the Pakistan Centre for Renewable Energy Technologies (PCRET) has played a crucial role in advancing biogas technology in the country [15]. The PCRET has been actively involved in the installation of over 1600 biogas plants, contributing significantly to the expansion and adoption of this sustainable energy source throughout Pakistan [15].

Furthermore, various non-governmental organizations (NGOs) have been instrumental in promoting and implementing biogas projects in both rural and urban areas of the country. Organizations such as IRSD, Koshis, and Green Circle Organization [15] have actively supported the installation of biogas plants, leveraging their expertise and resources to facilitate the adoption of this technology in diverse communities. Since the past decade, Revgreen Pakistan has also contributed to the increase in the overall Biogas Digester installation in Pakistan. Revgreen Pakistan is a key player in biogas plant construction and operations and since 2009 the company has been working in this sector.

Among the different designs available for biogas plants, the floating drum design has emerged as the most used in Pakistan [15]. This design offers practical advantages, demonstrating reliability and efficiency in biogas production. However, the Chinese fixed-dome design was also piloted in the country, although it encountered significant challenges [15]. Reports suggest that the Chinese design pilot biogas plants experienced persistent issues with leakage and seepage, ultimately leading to suboptimal performance. Additionally, the gas pressure generated by these plants remained low, further hindering their success [10][15].

2.6 The Problem with the Current Biogas Digesters Present in Pakistan

Floating drum design biogas plants are primarily installed for larger capacity outputs, although a few have been implemented for small household purposes in certain rural areas. However, it has been observed that this design often fails in the long run due to various reasons.

2.6.1 Inadequate External Frame and Drum Corrosion

One common issue encountered with the floating drum design is the absence or inadequate construction of the external frame meant to support the drum. As a result, the steel drum tilts to one side in many plants [15]. Over time, corrosion may lead to the development of holes in drums that have been in use for more than five years. To prevent gas leakage, these holes are typically patched using a mixture of dung and clay [15].

2.6.2 Water Accumulation in Gas Pipes

Another problem arises from the gas pipe connecting the drum to the kitchen, which is commonly made of plastic [15]. In numerous cases, this pipe is left unsecured and hanging, allowing water to accumulate at low points without a convenient way to remove it.

2.6.3 Insufficient Pre-Mixing Mechanism

The biogas stoves used in these plants are often adapted from natural gas or LPG stoves and lack a mechanism for pre-mixing the gas with air [15]. Consequently, the flames produced by these stoves may appear elegant but lack sufficient heat for effective cooking.

2.6.4 Lack of Clarity on Dung-to-Gas Ratio and Gas Requirements

Some NGOs involved in the construction of biogas plants have demonstrated a lack of clarity regarding the appropriate ratio of animal dung to gas production and the daily gas requirements of households. In one instance, an undersized digester was built, using a 10 m3 gas storage drum, to serve thirty families [15].

2.6.5 Incompatibility with Small Household Energy Needs

Most biogas digesters in Pakistan have high output capacities, making them impractical for typical household use [15]. This mismatch between capacity and demand renders them unfeasible for common domestic energy needs.

2.6.6 Complexity of Installation, Usage, and Maintenance

The installation, usage, and maintenance of biogas digesters are complex processes that require specialized knowledge. Consequently, only professional installers possess the necessary expertise to carry out regular maintenance, tune-ups, or new installations.

It is evident that while the floating drum design has been widely used, it presents several challenges and shortcomings that hinder its long-term success. This research paper aims to tackle these issues, by introducing the design for the tubular biogas digester with a portable container box.

2.7 Solution via the Tubular Biogas Digester Setup

The Design of the Tubular Biogas Digester with a Portable Container Box is put forward in this research. This design aims at reducing or rather diminishing, the drawbacks of its predecessor biogas digester systems that are already installed in Pakistan. The proposed design is specifically aimed at catering for the needs of a small household, particularly from the rural area. Its advantages over its predecessors are listed as follows:

2.7.1 Stability

This research integrates the design and usage of the container box. This container box ensures that the shape of the biogas digester is maintained throughout the process. The tubular biogas digester is designed to be housed underground, the container box will also provide adequate base and cushioning to it. The container box also prevents any damage on the tubular biogas digester by acting as its shield from potential cave ins and other external harming agents. Finally, it also eliminates the problem of tilting or instability commonly experienced with the floating drum design.

2.7.2 Durability

The container box helps increase the durability of the tubular biogas digester. It is itself made of PVC. Hence, unlike steel drums prone to corrosion, the container box does not succumb to corrosion. The tubular biogas digester itself is typically made of durable materials such as high-density polyethylene (HDPE) Geomembrane, ensuring a longer lifespan and minimizing the risk of holes or leaks.

2.7.3 Water management

The compact nature of the tubular biogas digester allows for its installation near the kitchen of a small household. This proximity reduces the length of the gas pipe between the digester and the kitchen, significantly lessening the probability of water accumulation. The portable container box, equipped with proper drainage mechanisms, ensures efficient water management, preventing potential damage or blockages caused by water and ensuring a more efficient gas flow.

2.7.4 Efficient combustion

Tubular biogas digesters often come with specially designed burners that enable proper pre-mixing of gas with air, resulting in improved combustion efficiency. This feature enhances the heat output of the biogas stove, making it more suitable for cooking purposes.

2.7.5 Scalability

Tubular biogas digesters is designed in an optimum capacity for a typical small household; hence these systems are better suited for household use. By providing an optimum option for a typical scenario, the tubular design ensures that biogas plants are appropriately sized to meet the specific needs of individual families or small communities.

2.7.6 Simplified maintenance

The design of the tubular digester, coupled with the use of a portable container box, simplifies installation, usage, and maintenance processes. The container box can be assembled easily in a puzzle like fashion, as the faces are “slide together” in a simple trapezoid shape, as opposed to being hammered together in complex shapes as that of the predecessors, hence the patriarch of the household can easily assemble it. The tubular biogas digester can be easily fitted inside it in a deflated manner. Due to this simplicity, the system is portable as well.

Summary

Biogas is a renewable energy source produced from the breakdown of organic matter by bacteria in an anaerobic environment. Anaerobic digesters facilitate the biogas production process by providing optimal conditions for bacterial activity. Biogas consists mainly of methane and can be used as an energy source, while digestateis a nutrient-rich fertilizer. Tubular biogas digesters are a simple and affordable type of digester suitable for households and small farms. They have a long, tube-like shape that promotes efficient gas production. Tubular digesters offer several advantages over other digester types for household use, including continuous feed, higher gas production rates, versatility in handling different waste sources, compact design for limited space, lower construction costs, ease of installation, lower maintenance requirements, reliable gas supply, adaptability to varying waste quantities, and scalability for different household sizes. The tubular digester design provides an appropriate solution for producing biogas to meet the energy needs of households and small farms in a sustainable and cost-effective manner, while also enabling effective organic waste management.

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Chapter 3: Relevant Methodologies Available

3.1 Component Design

The low-cost tubular biodigester system consists of two key components: the digester unit and the installation container, which houses the digester. To design and set up the low-cost tubular biodigester system, one needs to have knowledge about the essential parameters of both the digester and the container. It is also crucial to match the size of the digester with that of the installation pit for efficient biogas production. In this section, we present and explain the key parameters for consideration during the design of the low-cost tubular biodigester system. These parameters are classified as physical, process, and performance parameters.

3.1.1 Physical Parameters: Design

The low-cost tubular biodigester system consists of two key components: the digester unit and the installation pit, which houses the digester. To design and set up the low-cost tubular biodigester system, one needs to have knowledge about the essential parameters of both the digester and the pit. It is also crucial to match the size of the digester with that of the installation pit for efficient biogas production. In this section, we present and explain the key parameters for consideration during the design of the low-cost tubular biodigester system. These parameters are classified as physical, process, and performance parameters [8].

Physical parameters refer to the dimensions of the tubular biodigester, such as its length, diameter, and thickness of the plastic sheeting used to construct it. These dimensions are critical because they affect the total volume of the digester, which is then separated into two phases: liquid and gas. The liquid volume is supposed to fill the trench in which the digester is placed, and it is usually reported as 80% or 75% of the total cylindrical volume, depending on the author.

Process parameters relate to the operation of the low-cost tubular biodigester system. They include the hydraulic retention time (HRT), which is the time required for the substrate to remain in the digester to produce biogas, and the organic loading rate (OLR), which is the amount of substrate added to the digester per unit volume of the liquid phase. These parameters are crucial for efficient biogas production and depend on the characteristics of the substrate and environmental conditions.

Performance parameters are also introduced and described as indicators of the operational status of the low-cost tubular biodigester system. These parameters include the biogas production rate, which is the amount of biogas produced per unit volume of the digester per day, and the methane content in the biogas, which is a measure of the quality of the biogas produced.

For the physical parameters specification of the low-cost tubular biodigester, the dimensions of the biodigester, as well as the installation pit, are to be given importance. In this article, as we are dealing with a tubular design, the plastic polymer tube is lowered inside an installation pit [8]. The installation pit in the low-cost tubular biodigester provides several advantages. Firstly, it allows for better insulation of the digester, which in turn provides a stable and consistent temperature for the bacteria to thrive and generate biogas. Secondly, the pit helps to protect the digester from environmental factors such as extreme weather conditions and animal interference. Thirdly, the biogas is produced and stored inside the main digester body, hence diminishing the need for a separate storage container for the gas, this is turn, improves the gas expulsion/ effluent rate. It also reduces the overall cost of the system [11].

In the past, authors used an outdated method to determine the design of the reactor which yielded suboptimal results. The cylindrical volume of the tubular plastic was used as the central parameter and the total volume was separated into liquid and gas phases. The liquid volume was then reported as either 75% or 80% of the total cylindrical volume, and the dimensions of the trench were given as "recommended" without proper methodology or justification. However, the dimensions of the trench play a crucial role in determining the real liquid volume and, in many cases, the recommended dimensions are not consistent with the circumference of the plastic. This resulted in a loss of hydraulic retention time

(HRT) ranging from 6% to 51% compared to the HRT expected by the design. Additionally, biogas pressure was found to influence the final HRT, which resulted in a reduction of between 15% and 17% compared to the theoretical value expected by design. These issues highlight the importance of using a more efficient and accurate method to determine the dimensions of both the biodigester and the installation pit in the low-cost tubular biodigester [7].

To achieve this goal, the front-face schematic as per Figure 3-1 for the tubular design is suggested [7]:

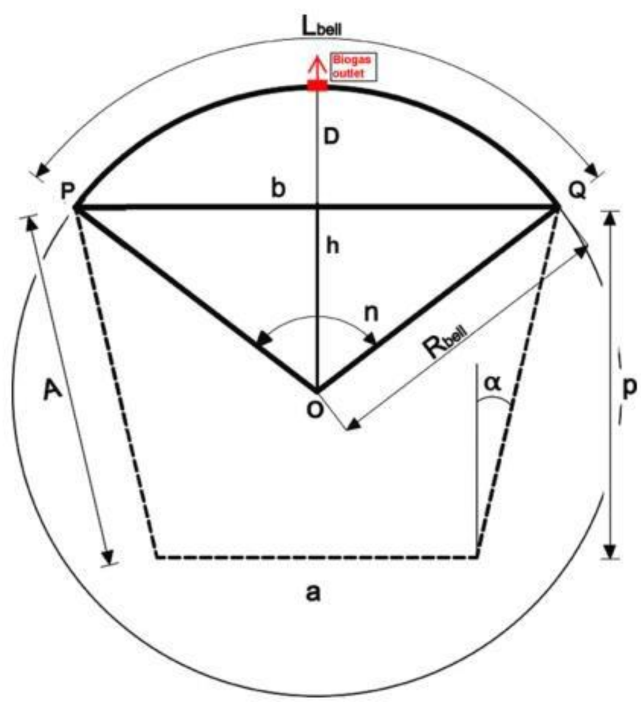

Figure 3-1. Schematic of Model's Front Face [7]

The upper area which is enclosed by the LBell arc is where the biogas produced will be stored during the whole process. At the top is where the Outlet is placed. From here the biogas will be siphoned off. This whole area is called the "Bell Area". The lower trapezoid shape indicates the shape of the trench in which the digester is placed. As per the image, the lower part of the digester will take on the shape of the trench. Due to this the overall total volume of the digester, V_{BD} will be divided into two halves (the Bell Area and the Trench).

As per Marti Herrero [7], the following equations were Put forward by the author. These equations lay the foundation for the calculation of accurate parameters imperative for the design.

$$V_{BD} = (CS_T + CS_B) \times L \quad (1)$$

$$CS_B = (p \times R_{bell} \times n/360) - (b \times h)/2 \quad (2)$$

$$CS_T = (p \times (b+a)/2) \quad (3)$$

$$C = 2 \times p \times r \quad (4)$$

$$C = 2 \times A+a+L_{bell} \quad (5)$$

Along with these equations, the author also put forward variables, the interpolation of which produced optimized formulae and values needed for this design.

$$F_b = b/r \quad (6)$$

$$F_a = a/r \quad (7)$$

$$Fp = p/r \quad (8)$$

$$F_{bell} = L_{bell}/r \quad (9)$$

After careful calculations and iterations, the author then found the values for the following variables that lead to the creation of a design, following which a biodigester can be produced that can theoretically produce 20% Biogas and 80% Liquid of the total volume.

$$F_{bell} = 1.2 \text{ and } \alpha = 7.5\,° \quad (10)$$

By keeping these values constant and using different values of circumference in the above equations (1) to (9), Table 3-1 was established [7].

Table 3-1. Dimensions of Biodigester with respect to the specific circumference of HDPE Plastic

C (m)	r (m)	a (m)	b (m)	p (m)	CS_{trench} (m^2)	CS_{bell} (m^2)	a (°)	L_{bell}
2	0.32	0.39	0.52	0.49	0.223	0.0538	7.5	1.2
2.5	0.4	0.49	0.65	0.61	0.348	0.0841	7.5	1.2
3	0.48	0.58	0.78	0.73	0.496	0.1211	7.5	1.2
3.5	0.56	0.68	0.91	0.86	0.684	0.1649	7.5	1.2
4	0.64	0.78	1.04	0.98	0.892	0.2154	7.5	1.2
5	0.8	0.97	1.3	1.22	1.385	0.3365	7.5	1.2
8	1.27	1.56	2.08	1.96	3.567	0.8615	7.5	1.2
7	1.11	1.36	1.82	1.71	2.719	0.6596	7.5	1.2
14	2.23	2.73	3.63	3.43	10.907	2.6384	7.5	1.2
1.4	0.22	0.27	0.36	0.34	0.107	0.0264	7.5	1.2
2.8	0.45	0.55	0.73	0.69	0.442	0.1055	7.5	1.2
4.2	0.67	0.82	1.09	1.03	0.984	0.2375	7.5	1.2
5.6	0.89	1.09	1.45	1.37	1.74	0.4221	7.5	1.2

The constant value of F_{bell} is the minimum value of the variable at which the slurry inside the biodigester does not clog up, hence ensuring a continuous flow system [7]. The constant value of the alpha angle ensures the shape of the trench is easily attainable and that which leads to the maximum biogas output.

3.1.2 Process Parameters: Design

Process parameters relate to the operation of the low-cost tubular biodigester system. They include the hydraulic retention time (HRT), which is the time required for the substrate to remain in the digester to produce biogas, and the organic loading rate (OLR), which is the amount of substrate added to the digester per unit volume of the liquid phase. These parameters are crucial for efficient biogas production and depend on the characteristics of the substrate and environmental conditions. The design of a low-cost tubular biodigester is a crucial step toward achieving efficient biogas production. Along with the Physical Parameters, the Operational Parameters are also necessary to ensure the optimal performance of the designed biodigesters. Several operating parameters are necessary to be considered to ensure the optimal performance of the biodigester [8]. These Are:

HRT: The Hydraulic Retention Time (HRT) is a crucial operating parameter in the design and operation of low-cost tubular biodigesters. HRT refers to the amount of time the influent, or the feedstock, remains inside the digester before being discharged. The calculation of HRT is an essential aspect of the design process and can be done using the Equation.

$$R = V_d / Q \tag{11}$$

Here, R represents the retention time, V_d is the volume of the digester, and Q is the influent flow rate.

It is important to note that the design value of R must be at least twice the growth rate of the methanogenic bacteria involved in the anaerobic process. Methanogenic bacteria play a critical role in the production of biogas by breaking down organic matter in the absence of oxygen. They are, however, the slowest growing microorganisms in the consortium. Hence, the HRT must be carefully considered to avoid washing out these bacteria from the digester and disrupting the biogas production process [15].

Therefore, a balance must be achieved between the required retention time and the rate of methanogenic bacteria growth to ensure optimal biogas production.

Organic Loading Rate (OLR): The Organic Loading Rate (OLR) is an important operating parameter for the design of a biodigester. It represents the number of volatile solids that are fed into the digester and is measured in kilograms (kg). In order to determine the OLR, the total solids (TS) fed into the digester must be determined alongside the corresponding volatile solids (VS). The OLR can be calculated using Equation OLR = %TS * %VS * m, where m is the mass of feedstock fed into the digester per day (kg/d), and %VS is the percentage of volatile solids in the influent [8].

The relationship between %TS and %VS is an empirical one and depends on the nature of the feedstock used for biogas production. Another equation that can be used to determine the OLR is OLR = Vd/Rd, where Vd is the volume of the liquid phase of the digester in cubic meters (m3) and Rd is the retention time in days.

A higher OLR leads to higher biogas production, but it may also lead to instability in the biodigester [15].

Temperature: The consortium of anaerobic bacteria plays a vital role in the biogas production process within the tubular biogas digester and its functionality is greatly affected by the temperature within the digester. Various groups of bacteria survive within specific temperature ranges [8][15]. Therefore, the design of the tubular biodigester takes into account the temperature range that the anaerobic bacteria can survive within. Specifically, the tubular biodigester is designed to operate within the mesophilic range of temperature which is between 20˚C - 45˚C [8].

In order to maintain a stable temperature within the tubular biodigester and insulate it from wide temperature fluctuations at low cost, the digester is placed in an excavated installation pit in the ground. The installation pit is constructed such that part of the digester is exposed to the ambient environment, allowing it to receive heat. However, the digester is designed to operate at ambient temperature, meaning that it is not actively heated or cooled beyond the heat transfer that occurs through the installation pit. This design allows for a stable and consistent temperature range within the mesophilic range, which optimizes the efficiency of the anaerobic bacteria and therefore maximizes biogas production.

pH: The pH level in the tubular biodigester plays a crucial role in determining the efficiency of methane production by the consortium of microorganisms involved in the anaerobic process [15]. It is important to maintain the pH level within a specific range as it affects the activity of the bacteria. The optimal pH range for the digestion process is 6.5

- 7.5. The pH level in the digester can be maintained by controlling the type of substrate used, the operating temperature, and OLR [15].

For small-scale digesters, the pH level is not always a critical parameter in the design of the digester. This is because small-scale digesters often use a single substrate source and the pH level can be easily controlled by adjusting the feedstock. However, for larger-scale digesters that process a variety of substrates, it is important to consider the pH level during the design process. If the pH level is not maintained within the optimal range, it can lead to a decrease in methane production and ultimately impact the efficiency of the biodigester.

Mixing: Mixing is an important operational parameter in the design of a tubular biodigester. Efficient mixing is essential to ensure a homogenous distribution of the substrate and to avoid the formation of scum layers and dead zones within the digester. This can be achieved through various mixing techniques such as mechanical, hydraulic, or gas mixing. [15]. The mixing rate can be influenced by the size and shape of the reactor, the type of substrate, and the operating temperature and OLR. However, for a low-cost tubular biodigester, the importance of mixing may be relatively low due to the self-mixing action of the biogas produced during the digestion process. The tubular design of the biodigester allows for the circulation of the substrate, which helps in achieving a uniform mixing. However, it is still important to consider the mixing efficiency in the design to ensure optimal performance and prevent potential issues.

Gas Pressure: Gas pressure is an important operational parameter to consider in the design of a tubular biodigester. The pressure inside the digester affects the biogas production rate and the overall efficiency of the system. The gas pressure is influenced by various factors, including the type and composition of the substrate, the loading rate, the temperature, and the gas production rate. [15]

In the design of a tubular biodigester, gas pressure needs to be carefully considered to ensure the proper functioning of the system. Maintaining an appropriate gas pressure is crucial for efficient biogas production and the stability of the anaerobic digestion process. Insufficient gas pressure can lead to a slower biogas production rate and poor mixing of the substrate, resulting in suboptimal performance. On the other hand, excessive gas pressure can cause gas leaks, system failure, or even damage to the biodigester structure [8].

For a low-cost tubular biodigester, the importance of gas pressure may vary depending on the specific design and intended use. In some cases, the self-regulating nature of the tubular biodigester, with its flexible and expandable design, can accommodate fluctuations in gas pressure to a certain extent. However, it is still important to consider gas pressure in the design to ensure efficient gas production and safe operation of the biodigester. Proper gas pressure monitoring and control mechanisms should be implemented to maintain optimal conditions within the biodigester and maximize biogas production [8].

3.1.3 Container Box: Design

The container box for the biogas digester is made of uPVC due to its strength, malleability, lightweight nature, and cost-effectiveness. The box is designed with interlocking pieces, using tongue and groove joints to connect the sides and a box joint to attach the base securely. Skilled craftsmen carefully cut the uPVC material to the required dimensions, ensuring a precise fit. The tongue and groove joints are created meticulously, ensuring a tight and seamless connection between the sides. Additional reinforcing elements, like corner braces and supports, may be incorporated to strengthen critical areas and improve the overall durability of the container box. The resulting assembly provides a secure and airtight enclosure for the biogas digester, allowing for optimal performance and preventing any leaks or structural weaknesses. The overall assembly of the model with the container box is as follows:

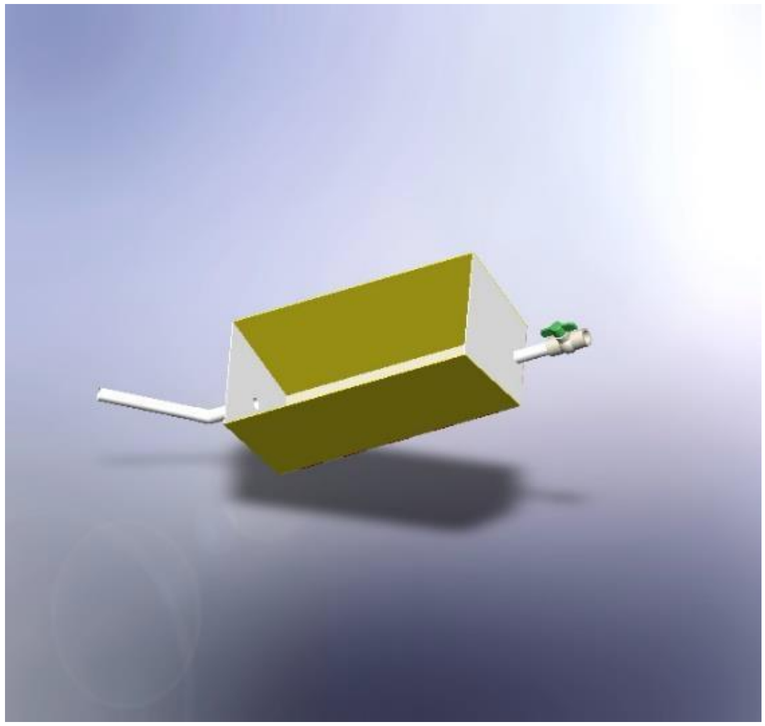

Figure 3-2. Overall Assembly

As per the image, the container box is divided into the following categories:

a. Inlet Assembly
b. Outlet Assembly
c. Main Container Assembly

3.1.3.1 Inlet Assembly

The inlet assembly is comprised of a practical combination of uPVC pipes and an elbow, designed to effectively transport the slurry into the biogas digester. Due to the closed nature of the trench wall, the slurry cannot be injected from the side, necessitating a top-down introduction.

To ensure a smooth flow without blockages, the pipe is slanted at an appropriate angle, 25 Degrees [17]. This slant prevents any potential obstructions from accumulating inside the pipe, allowing the slurry to move unhindered.

The dimensions of the inlet assembly are given in Table 3-2, whereas the pictorial depiction is given in Figure 3-3.

Table 3-2. Dimensions of the Inlet Assembly Constituents

Ser.	Large Pipe Length (m)	Small Pipe Length (m)	Diameter of Pipes (m)	Thickness of Pipes (m)	Diameter of Elbow (m)	Thickness of Elbow (m)
1.	0.8	0.4	0.1	0.609	1.609	0.609

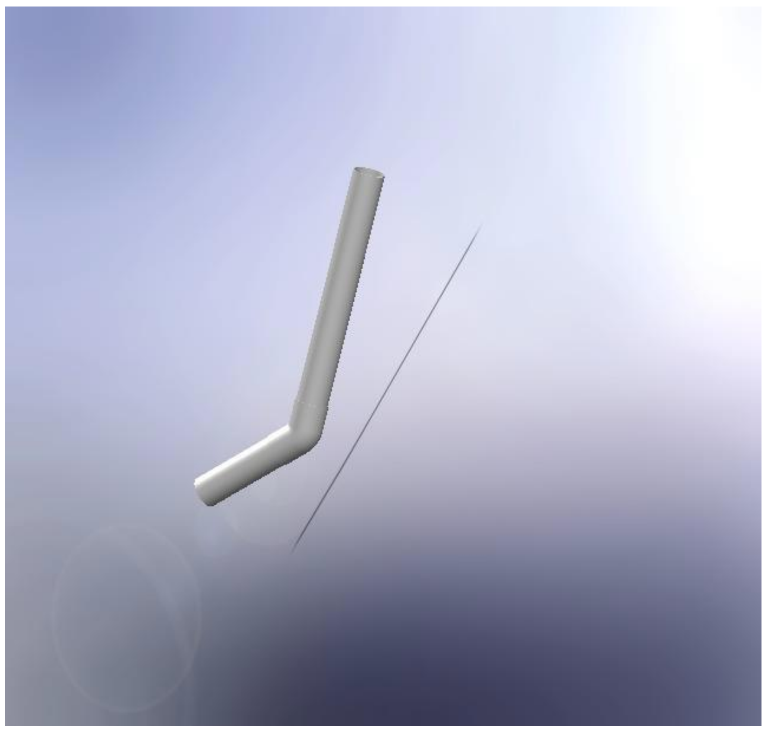

Figure 3-3. Inlet Assembly

3.1.3.2 Outlet Assembly

The outlet assembly comprises a uPVC pipe and a Ball Valve, serving the purpose of conveying the slurry from the biogas digester. This assembly is connected to the digester at a lower level, allowing for effortless extraction of the slurry through gravity-induced flow.

To regulate the slurry flow, a Ball Valve is installed in the assembly. This valve effectively controls the rate at which the slurry is discharged, ensuring that the desired retention time is maintained within the digester. By adjusting the valve, operators can manage the flow according to the specific requirements of the system.

The dimensions of the inlet assembly are given in Table 3-3, whereas the pictorial depiction is given in Figure 3-4.

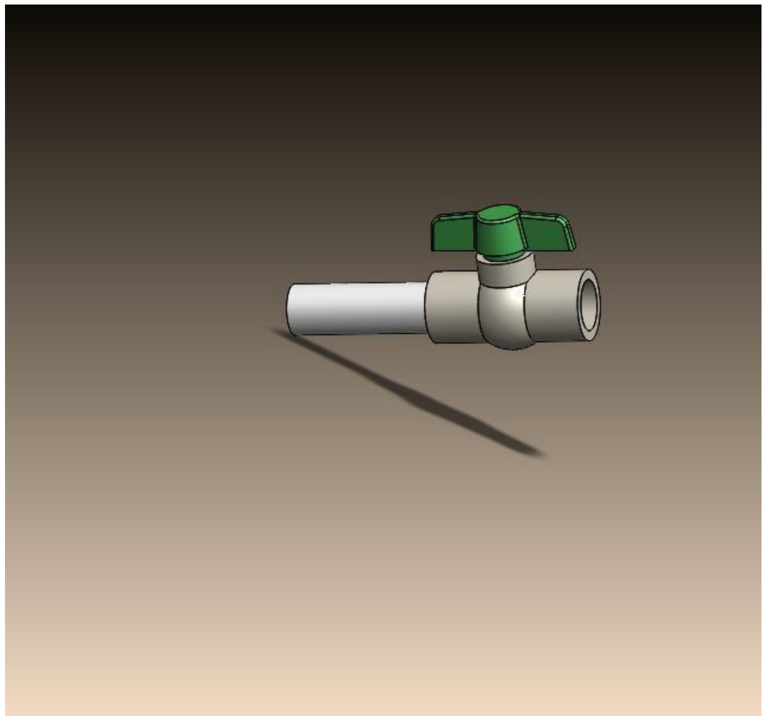

Figure 3-4. Outlet Assembly

The properties of this assembly are as follows:

Table 3-3. Dimensions of the Outlet Assembly Constituents

Ser.	Pipe Length (m)	Pipe Diameter (m)	Pipe Thickness (m)	Ball Valve Diameter (m)	Diameter of Elbow (m)	Ball Valve Thickness (m)
1.	0.4	0.1	0.609	1.609	0.2141172	0.4

3.1.3.3 Main Container Box Assembly

The assembly serves as the complete enclosure for the biogas digester body and comprises five uPVC sheets. Four of these sheets are connected to each other using the tongue and groove joint type, while the fifth sheet serves as the base and is attached to the rest of the sheets via a box joint type.

The use of tongue and groove joints allows for easy disassembly and reassembly of the structure. This joint type simplifies the process and eliminates the need for permanent joints, offering convenience and flexibility. Additionally, joining the sheets with tongue and groove joints does not require extensive expertise, making it accessible to assemble the structure.

The front and back face sheets are designed with tongues, while the side sheets feature grooves. This arrangement ensures a snug and secures fit when the sheets are connected, enhancing the overall stability of the assembly.

The pictorial depiction is given in Figure 3-5.

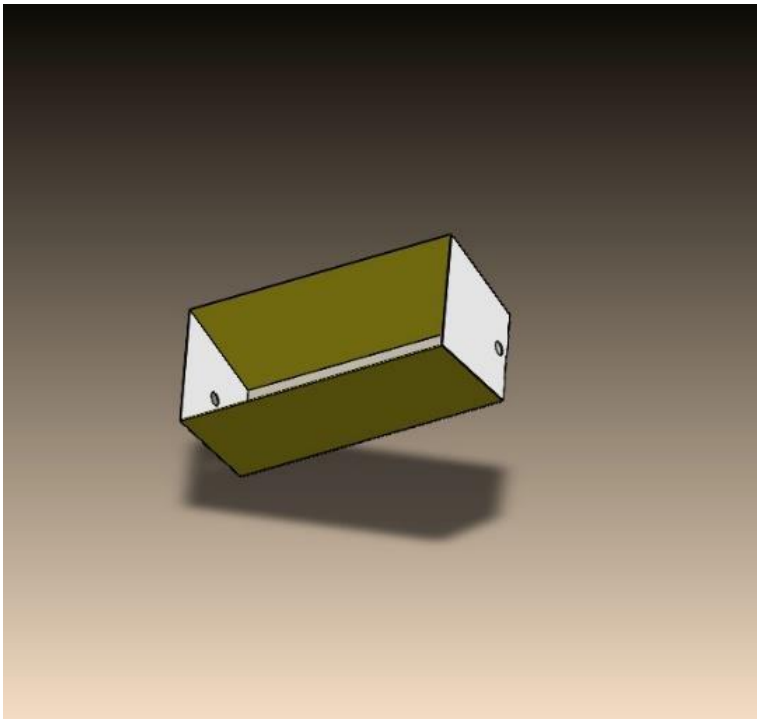

Figure 3-5. Main Container Box Assembly

The pictures of the tongue, groove, and box element are as follows:

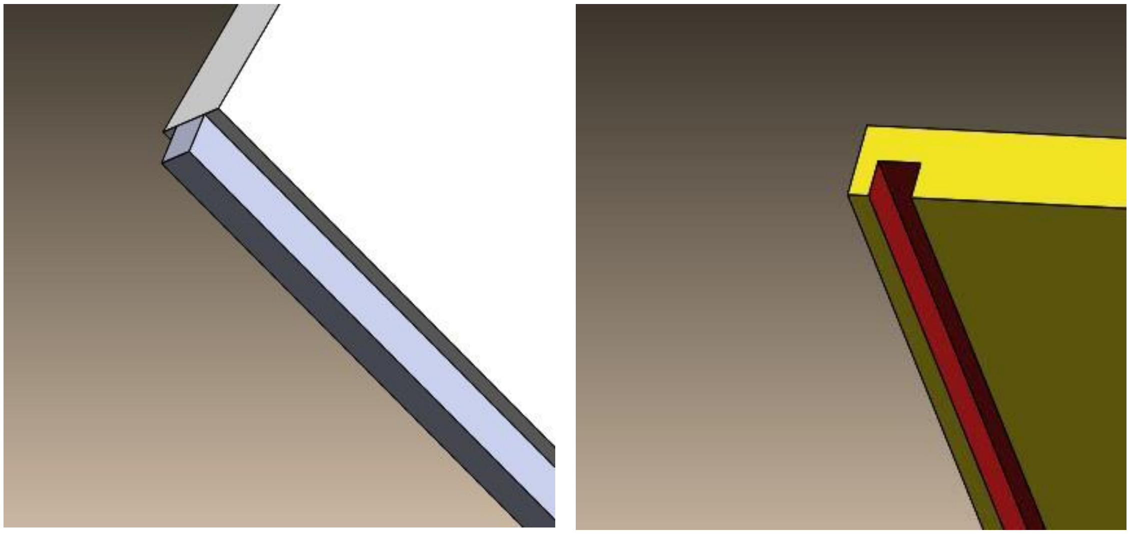

Figure 3-6. (Left) Tongue Protrusion on the Front and Back face; (Right) Groove Depth on the Side Faces

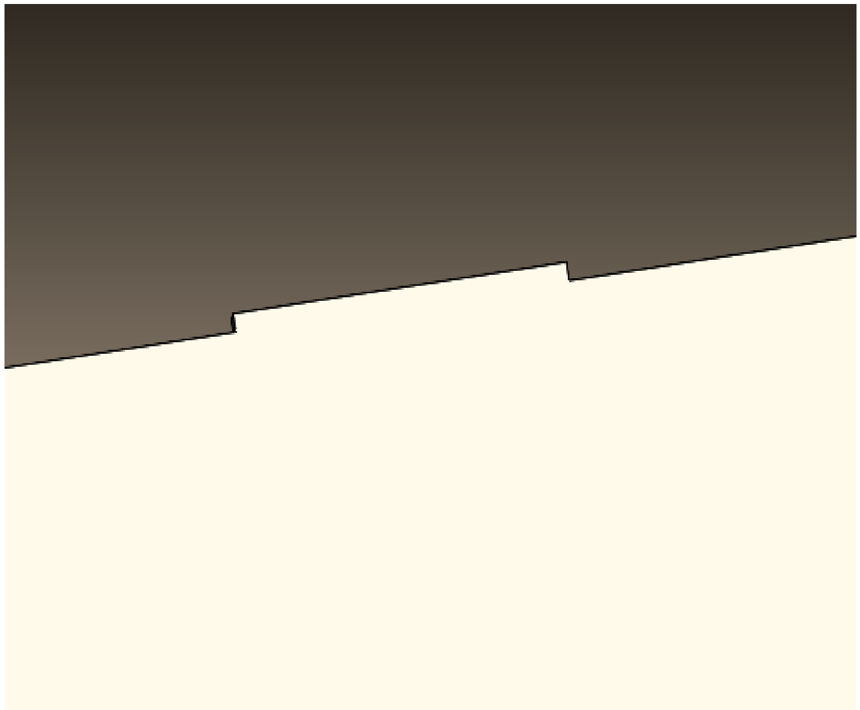

Figure 3-7. Box Protrusion on the Base

The properties of this box are given in per table. Other miscellaneous properties are given as follows:

Table 3-4. Dimensions of the Main Constraint Box Assembly Constituents

Ser.	Tongue Length (m)	Groove Depth (m)	Box Length (m)
1.	0.005	0.005	0.01

Summary

Several key physical, process, and performance parameters are important to consider in the design to optimize biogas production. The physical parameters include the dimensions of the digester tube and installation pit. The installation pit provides advantages like insulation, protection from the environment, and reducing the need for a separate gas storage container.

The process parameters include hydraulic retention time (HRT) and organic loading rate (OLR). The HRT must be long enough for the methanogenic bacteria to grow, while the OLR affects biogas production. Other parameters like temperature, pH, mixing, and gas pressure also impact biogas production and must be considered in the design. A stable temperature within the mesophilic range optimizes bacteria efficiency. An optimal pH range of 6.5 to 7.5 is needed. Mixing ensures homogeneous substrate distribution and gas pressure should be maintained at an appropriate level.

The container box for the digester is made of uPVC and uses interlocking pieces with tongue and groove joints. The inlet assembly introduces the substrate into the digester at an angle to prevent obstructions. The outlet assembly uses a valve to control the discharge of the substrate and maintain the HRT. The main container box assembly encloses the digester body using tongue and groove joints for easy assembly and disassembly.

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Chapter 4: Analysis, Results and Discussion

4.1 Biogas Digester (Physical Parameters)

For the validation of this tool, an empirical result correlation with results from another article [3] will be done. By doing this correlation, we will be mathematically designing a tubular digester system that can theoretically produce the output given in the selected article [3].

This study [3] was conducted at the dairy farm, Faculty of Veterinary Sciences, PMAS-Arid Agriculture University, Rawalpindi. The biogas digester was designed with a methane production capacity between 0.7 and 0.8 m3 daily. The substrate used in the study was Buffalo Dung (BD), and its mixtures (with Cow Dung and SW) which were mixed with water to create a slurry. The initial parameters used in the study included a total solid (TS) content of 10%, water to substrate ratio (W/S) of 1:1, and inoculum-to-substrate ratio (I/S) of 1:2. The results showed that the biogas digester was able to produce an average of 0.25 m3 (Maximum 0.42 m3) of biogas per day with a methane content ranging from 55% to 65%. Additionally, after 30 days, the biogas production rate increased to an average of 0.35 m3 per day with a methane content ranging from 60% to 70%. The study also investigated the effects of different feeding materials on biogas production, including buffalo dung (BD), buffalo dung plus chicken droppings (BD + CD), and buffalo dung plus sheep waste (BD + SW). The results showed that all three feeding materials were effective for biogas production. The key takeaways from this study include:

a. A TS content of 10%, W/S ratio of 1:1, and I/S ratio of 1:2 can be used as initial parameters for biogas production.
b. Biogas production can provide renewable energy for households in rural areas.
c. Further research is needed to optimize the design and performance of fixed dome-type small-size portable biogas digesters for domestic use.

d. Overall, this study provides valuable insights into the use of cow dung as a substrate for biogas production in small size household portable Biogas Digesters for domestic use in rural areas of Pakistan. The results suggest that fixed dome-type small size portable biogas digesters can be an effective and sustainable solution for providing renewable energy to households in rural areas.

From this article, the case pertaining to Buffalo Dung only is selected for the study. Properties surrounding this substrate are given as follows.

Table 4-1. Buffalo Dung Properties

Ser.	HRT	Substrate	Solid Loading Rate (Kg/Day)	Max Biogas Production per day (m3/Day)	Total Biogas Production for 30 Days (m3)	W/S Ratio	Dome Biodigester Volume (m3)
1.	30 Days	Buffalo Dung	20	0.42	12.63	3:1	2.15

The W/S Ratio has been changed from 1:1 to 3:1. The reason for this change is that we are shifting the focus of the study from the Dome type Biodigester to the Tubular Biodigester. In the Tubular Biodigester, the continuous flow of the slurry is maintained [8]. To ensure this continuous flow, the mixture is kept in an abundantly liquid state.

The volume of the Dome Biodigester is 2.15m^3. Hence to match the Physical characteristics of both cases, the tubular biodigester that is to be designed is also taken to be of 2.15 m^3 capacity.

As per discussion in para 2.1, 20% gas and 80% liquid ratio is recommended for the tubular biodigester to perform optimally. Hence if the complete biodigester internal volume is in use, then theoretically the biogas volume that should be produced by the tubular biodigester is:

$$V_{tbd} = 2.15*20/100 = 0.43\ m^3 \tag{12}$$

Hence, $V_{tbd} = 0.43\ m^3$ will be the volume of Biogas that can be theoretically produced by the Tubular Biodigester. In the previous case, the total biogas produced by the dome digester with an HRT of 30 Days was 12.64 m^3. Hence:

$$12.63/30 = 0.42\ m^3 \tag{13}$$

From this, it is seen that the dome biodigester produces 0.42 m3/day of biogas, the theoretical production for the tubular digester is 0.43 m3, hence we can move forward.

Now the dimensions for the trench and the tubular digester need to be calculated. The minimum HDPE that can be ordered in Pakistan in of 300 sqm, hence we can easily design our tubular biodigester with a circumference of up till 300 sqm. But as we are designing the biodigester for an average Pakistani home, and our minimum volume requirement is 2.15 m3, hence HDPE of Circumference 4m can easily suffice. By using this value and substituting it in the equations mentioned above, we can get the following values.

Table 4-2. Dimension for the Idealistic Biogas Digester Assembly

Ser.	F_{bell} (m)	α (°)	Circumference (m)	N Angle (°)	a (m)	b (m)	p (m)	R_{bell} (m)	CS_{bell} (m)	CS_{trench} (m)	Length (m)	L_{bell} (m)	A (m)
1.	1.2	7.5	4	118	0.78	1.04	0.98	0.606649	0.216497	0.8918	1.939913	1.249387	0.985306

Once the Biogas production starts, the gradual biogas pressure builds up inside and affects the biogas production of the reactor. An increase in the inside pressure causes the HRT to decrease, with an increase in biogas production and a decrease in water volume. But for a sustainable system to flourish, the stated HRT needs to be maintained. Hence the following equations are introduced to further cater for the pressure variation.

Various Authors agree that for tubular biodigesters, inside pressure build-up averages 980.64 Pa, which is equivalent to 0.1m of water column [7]. This is a theoretical approximation; the actual water volume loss can be measured via the specific measuring tool after the manufacture of the tubular digestor is complete. Now, new values of 'p' and 'b' are calculated as follows:

$$p' = p - h_p \tag{14}$$

$$b' = b - 2 \times h_p \times \tan\alpha \tag{15}$$

Hence using hp=0.1m, we get

$$p' = 0.88 \tag{16}$$

$$b' = 1.013 \tag{17}$$

using these values and substituting them in the formula of the CS_{trench} (CS_T), we get the new value of CS_T'

$$CS_T' = 0.78892 \tag{18}$$

To conserve the HRT and the liquid volume, the original value of 'L' is multiplied by the ratio CS_T/CS_T' [7]. The calculated value is the actual length, 'L'' of the tubular biodigester.

$$L' = L \times CS_T/CS_T' = 2.19289 \tag{19}$$

Hence the final table of values for the physical parameters is as follows:

Table 4-3. Dimension for the Realistic Biogas Digester Assembly

Ser.	**F_{bell} (m)**	**α (°)**	**Circumference (m)**	**N Angle (°)**	**a (m)**	**b (m)**	**p (m)**	**R_{bell} (m)**	**CS_{bell} (m)**	**CS_{trench} (m)**	**CS_{trench}' (m)**	**Length' (m)**	**L_{bell} (m)**	**A (m)**
2.	1.2	7.5	4	118	0.78	1.04	0.98	0.606649	0.216497	0.8918	0.78892	2.19289	1.249387	0.985306

Finally, the overall comparison of the biogas productions for both the biogas digesters is given in the following graph:

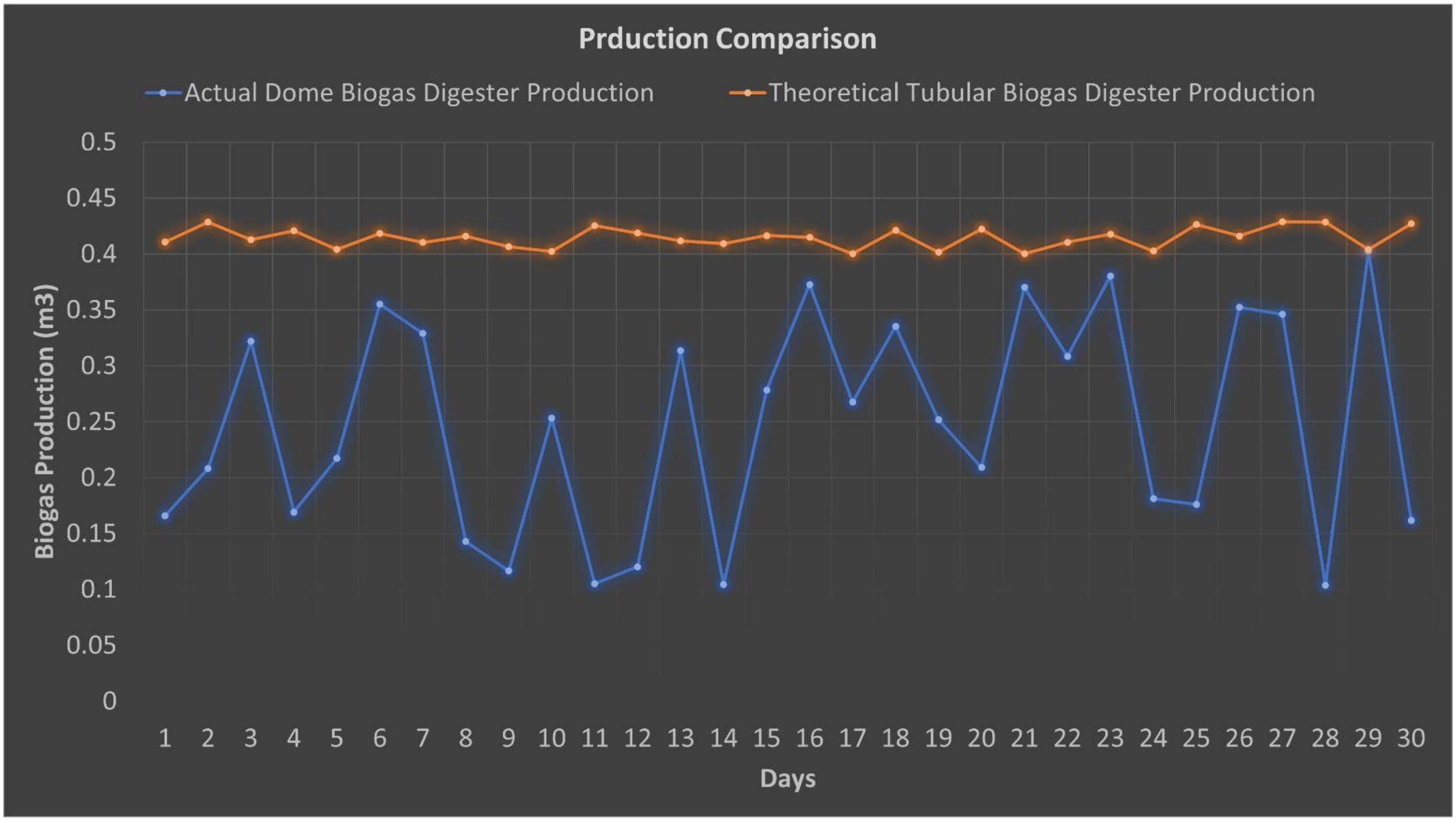


Figure 4-1. Comparison Graph between the two Biogas Digesters

The final outlook of the tubular biogas digester assembly is as follows:

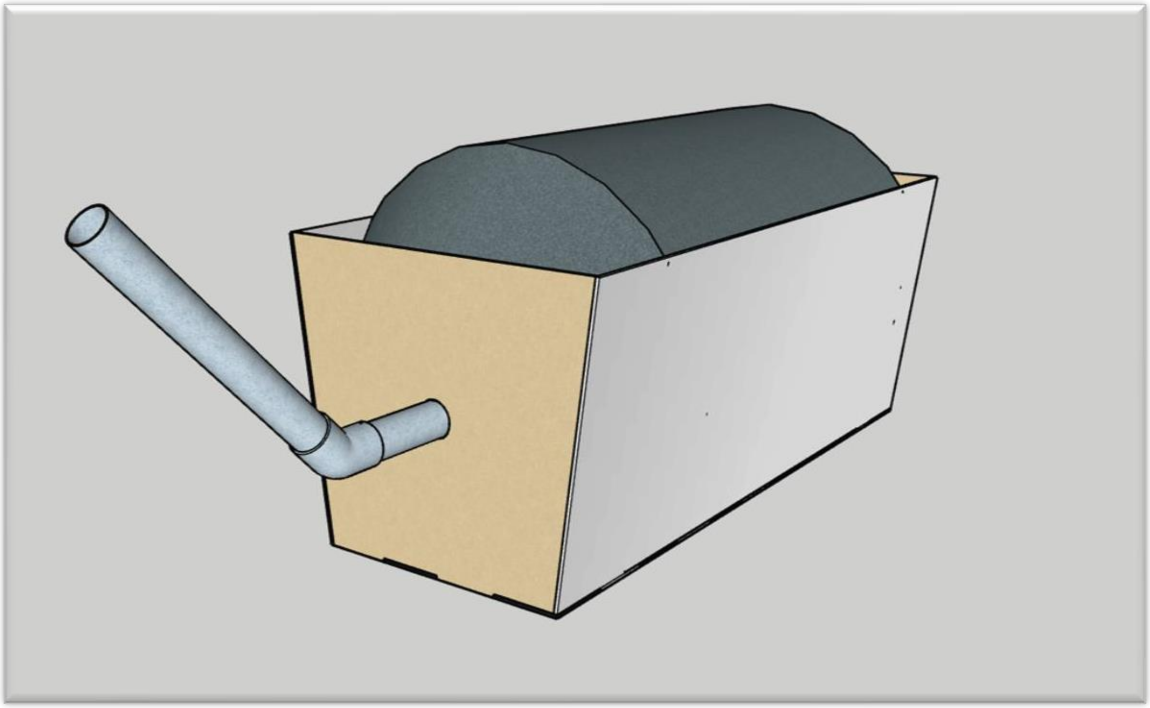


Figure 4-2. Final Overall Assembly

4.2 Biogas Digester (Operation Parameters)

To calculate the OLR of the process, we need the empirical values of the BD. These are given as follows:

Table 4-4. Empirical Values of Buffalo Dung

Ser.	**Feedstock**	**VS%**	**TS%**
1.	BD	85	25

Using these values and the formula, the OLR is calculated as

$$OLR=0.25 \times 0.85 \times 20=4.25 \tag{20}$$

4.3 Biogas Digester (Post-Manufacture Performance Parameters)

The performance parameters of a biogas digester system play a crucial role in evaluating its effectiveness and efficiency. These parameters include the biogas production rate, biogas productivity, biogas quality, and biodegradation rate. Specifically, for the application of biogas digester systems in rural communities, certain parameters such as the quantity of biogas produced, biogas production rate, and biogas productivity is essential for assessing the overall functioning of the system.

To determine the quantity of biogas produced on a daily basis, it is necessary to consider the specific local conditions. One common method used for this purpose is the installation of a gas flow meter within the gas convey pipeline of the biogas digester system. The gas flow meter allows for the measurement of the biogas flow, providing accurate readings of the amount of biogas generated.

To obtain consistent and reliable data, readings from the gas flow meter are typically taken at regular intervals, often every 12 hours. These intervals are usually timed to coincide with the feeding of the digester, as this is when biogas production is expected to be at its highest. By capturing the gas flow readings during the feeding process, a more accurate representation of the biogas production rate can be obtained.

The gas flow meter records the volume or flow rate of biogas passing through the pipeline, which is then used to calculate the quantity of biogas produced within a specific time period. This information is invaluable for assessing the performance of the biogas digester system, as it allows for the monitoring of its biogas production capabilities over time.

By regularly monitoring the quantity of biogas produced, the biogas production rate can be determined. This parameter indicates the rate at which biogas is being generated by the digester system.

The Biogas Production Rate can be found via the following equation:

$$\text{Production Rate (PR)} = m^3_{Biogas}/d$$
(21)

Additionally, the biogas productivity can be calculated by dividing the biogas production rate by the volume or mass of the feedstock used in the digester. This parameter provides insights into the efficiency of the system in converting organic waste into biogas. The equation is as follows:

$$\text{Productivity} = PR/kg_{VS} \quad (22)$$

It is important to note that the biogas quality and biodegradation rate are also significant performance parameters of a biogas digester system, but they may require different measurement techniques and considerations.

4.4 Container Box Analysis

To assess the container box model's structural performance, a thorough analysis was conducted using Solidworks 2023. The analysis focused on stress and factor of safety calculations, ensuring the box's design would meet the required standards.

For the analysis, the material selected in the software setup was "PVC Rigid." This material possesses specific properties that make it suitable for the container box. The properties of the said material are as follows:

Table 4-5. Properties of the Proposed Material

Ser.	Mass Density	Tensile Strength	Compressive Strength	Yield Strength	Thermal Expansion Coefficient	Thermal Conductivity	Specific Heat	Material Damping Ratio
1.	1300	40700000	75000000	52500000	70	0.147	1355	0.02

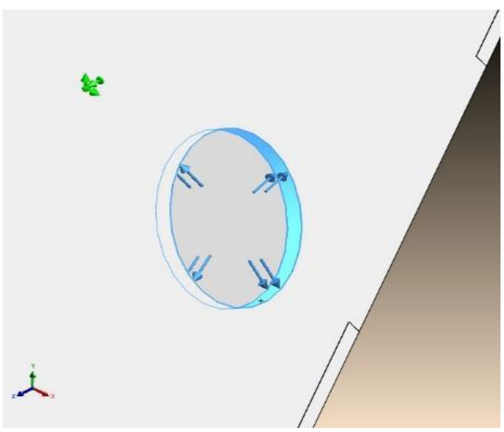
The a/m properties were selected as per the real-life stock of uPVC available in the local market. After completion of the model, the mass details of the categories are as follows:

Table 4-6. Mass Properties of the Proposed Model

Ser.	**Mass of Inlet Assembly (kg)**	**Mass of Outlet Assembly (kg)**	**Mass of Front and Back sheets (kg)**	**Mass of Side Sheets (kg)**	**Mass of Base (kg)**	**Total Mass of Main Container Assembly (kg)**	**Total Mass of Overall Assembly (kg)**
1.	2.42	7.81	20.78	50.86	55.10	126.74	136.97

4.4.1 Force Distribution

The analysis focused solely on the main container assembly. When examining the attachments of the inlet and outlet assemblies, the weight of each respective assembly was considered and applied as radial force distributions. The pressure distribution within the container reflects the force exerted by the biogas digester. As discussed earlier, the pressure magnitude amounts to 980.64 Pa [7]. The weight distribution is given in Figure 4-3 (Left and Right). The pressure distribution is given in Figure 4-4.



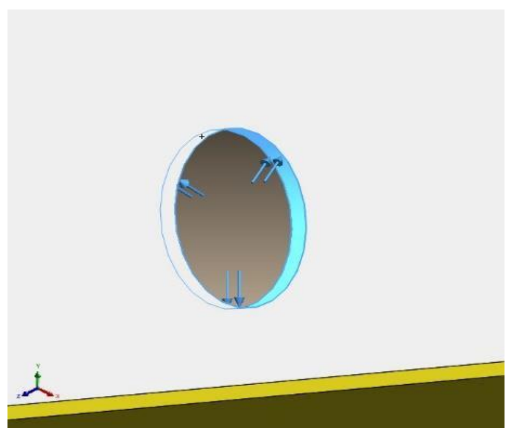


Figure 4-3. (Left) Outlet Assembly Port; (Right) Inlet Assembly Port

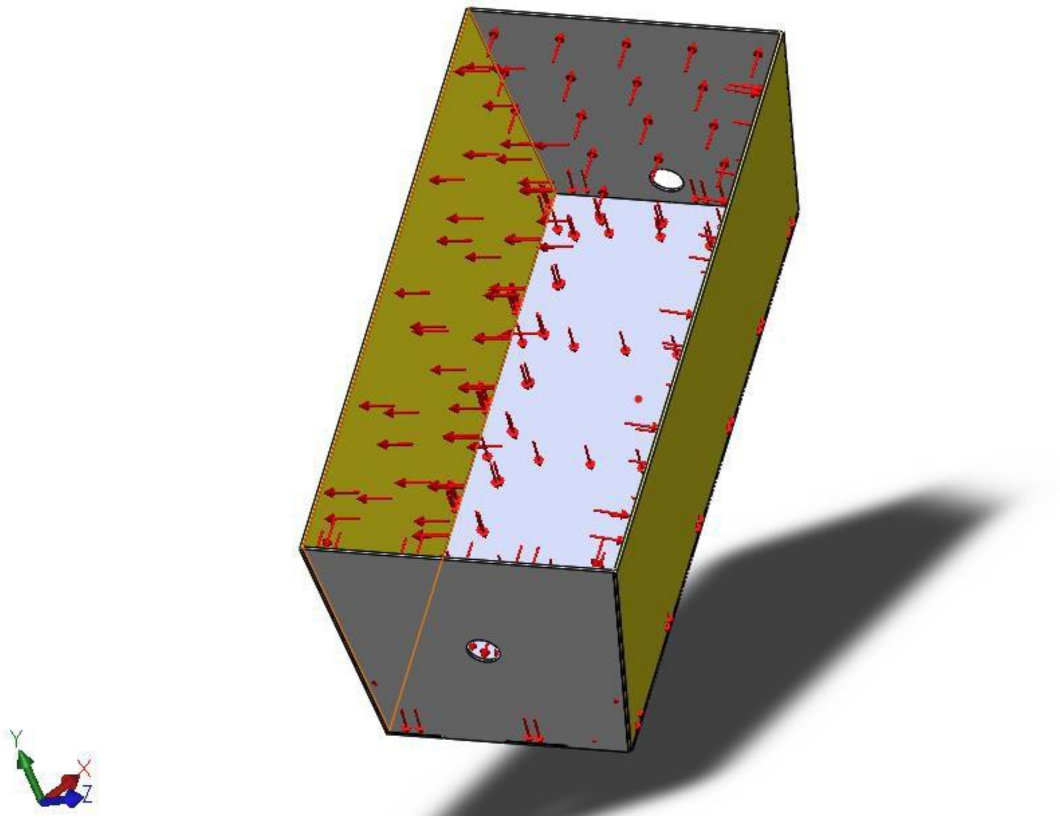


Figure 4-4. Container Box Pressure Distribution

4.4.2 Sheet Anchors

The main container assembly is anchored/fixed on the base sheet because the assembly will be placed on it inside the trench, hence it will be immovable. The side sheets have also been fixed because when the container box will be placed inside the trench, the side walls of the trench will be completely in contact with the side sheets. Hence the side sheets will be immovable as well. The back sheet is also fixed due to the same reason, the pipe that protrudes from the back sheet is buried under the soil. Another pipe can be attached to the ball valve that leads to a collector sack to collect the slurry after the HRT. These fixtures are shown in Figure 4-3.

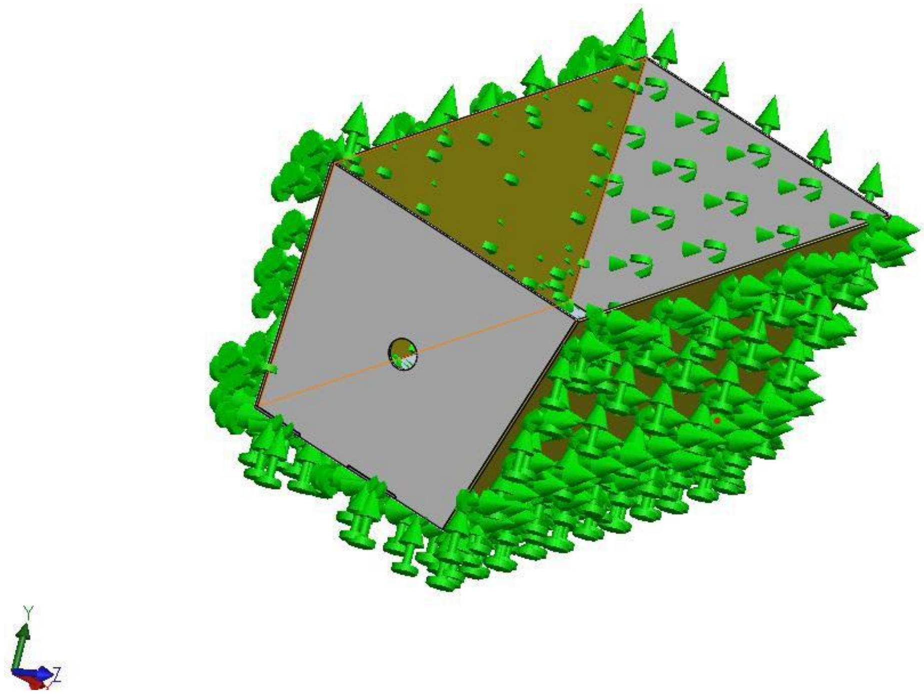


Figure 4-5. Side Fixtures

4.4.3 Joint Interactions

The container box is assembled using specific joint interactions to ensure stability and immovability. The tongue and groove joint is utilized to attach all four sides of the box securely. This type of joint creates a tight fit, preventing any movement or separation between the sides. Similarly, the base of the container box is connected to the sides using a box joint, which further enhances the immovability of the assembly. This joint type ensures a solid and compact connection between the base and the sides, mirroring the immovability of the components once the entire assembly is placed inside the trench.

4.4.4 Stress Analysis

When subjected to external forces and pressure, the container experiences internal stress. To analyze the distribution of this stress, SolidWorks software was utilized to generate a stress diagram. This diagram considers the weight of the inlet and outlet assembly, as well as the impact of biogas digester pressure on the container box. The overall stress analysis is shown in Figure 4-4.

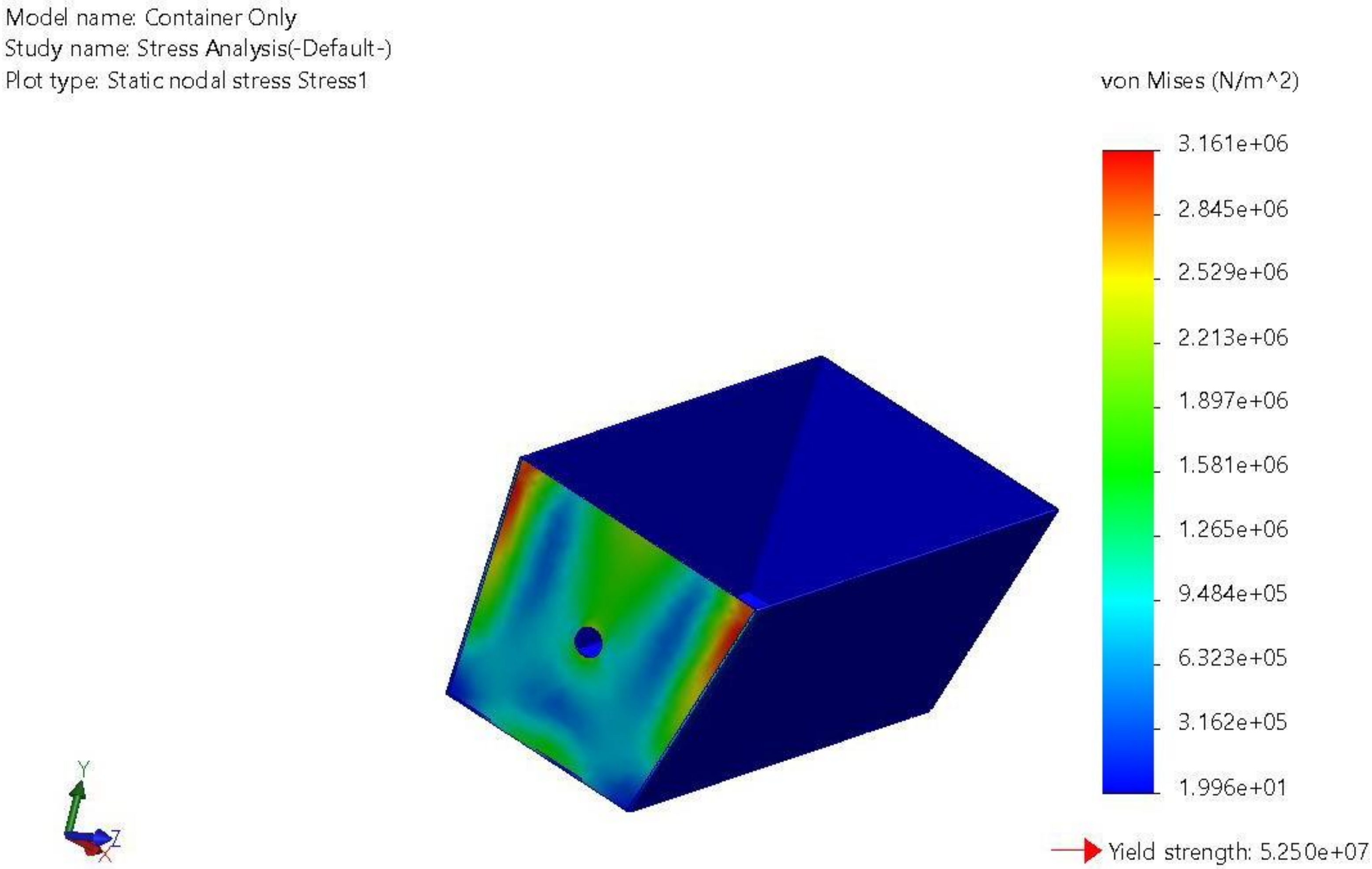


Figure 4-6. Overall Stress Analysis Plot

The stress categorization is as follows:

Table 4-7. Stress Categorization

Ser.	**Name**	**Type**	**Min (N/m^2)**
1.	Stress1	VON: von Mises Stress	12.67

The stress diagram reveals that the assembly experiences varying stress levels, ranging from 19.96 to 3.161 x 10^6 N/m^2. Notably, the front sheet of the assembly exhibits a significant gradient in stress compared to the other components. This disparity can be attributed to the fact that the front sheet is not fixed like the rest of the sheets. As a result, it bears a relatively higher level of stress compared to the other parts of the assembly, which experience relatively low stress. This disparity can be accurately depicted in the graph as follows:

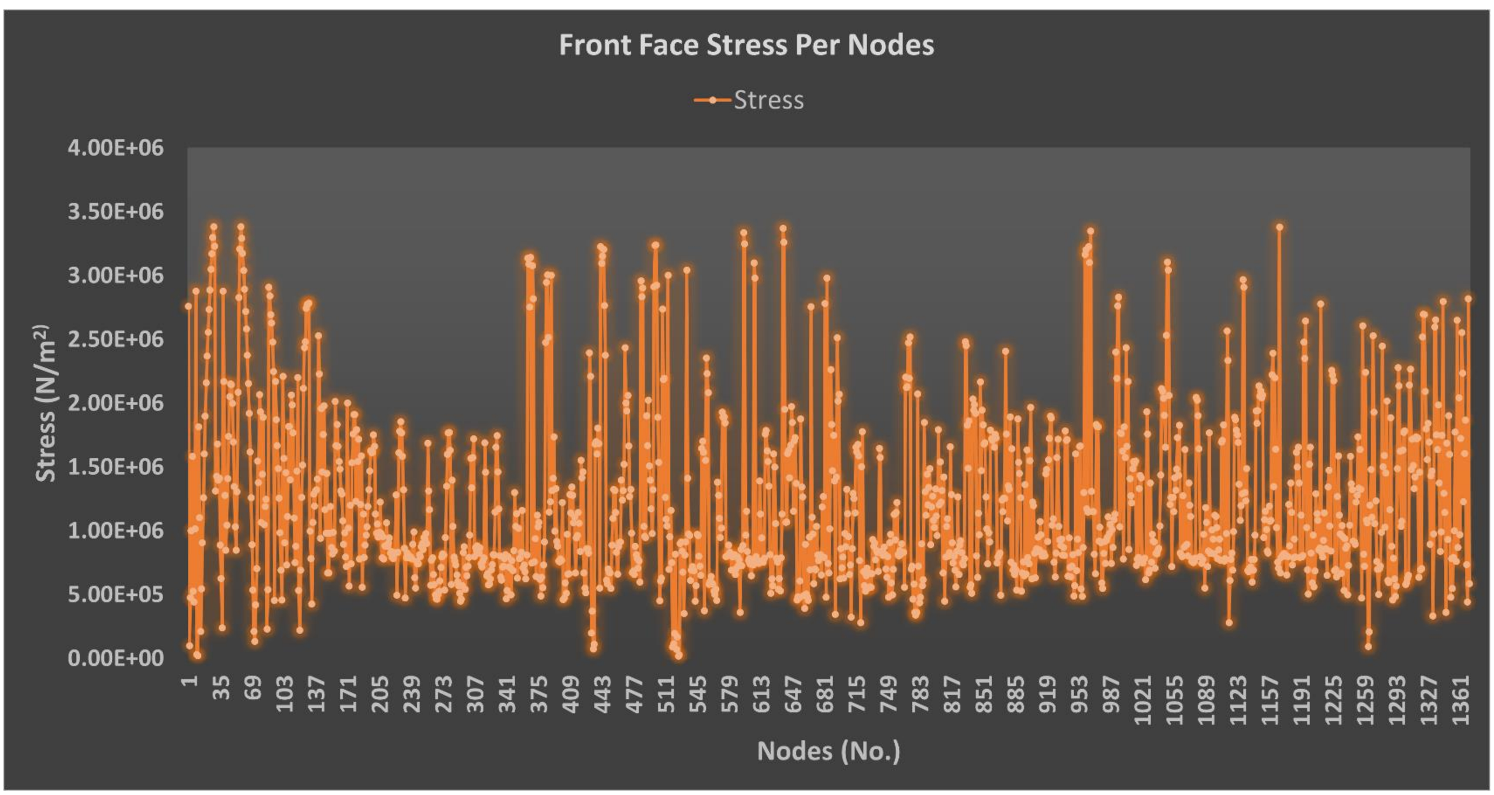


Figure 4-7. Graph for the Stress Influence per node on the Front Face

And the strain attributed to this stress influence is seen the following graph:

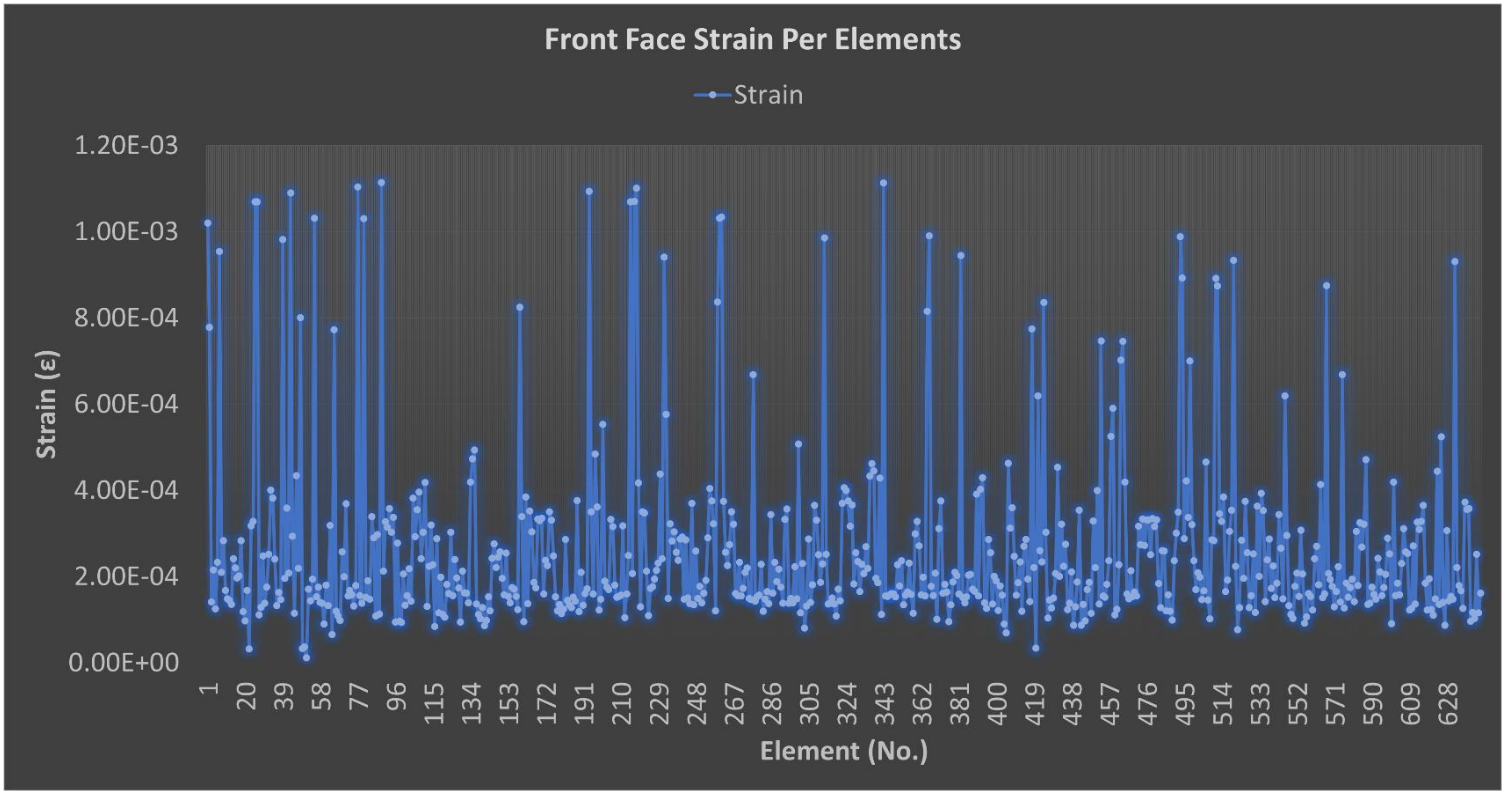


Figure 4-8. Graph for the Strain induced per element on the Front Face

Considering the yield strength of the material used, which is 5.25 x 10^7 N/m^2, it can be concluded that the assembly remains intact under the current force and pressure exerted. This observation suggests that the strength and durability of the assembly are more than sufficient to withstand the operational demands imposed by the biogas digester.

4.4.5 Factor of Safety (FOS) analysis

To validate the reliability and strength of this assembly, a Factor of Safety (FOS) analysis can be conducted using appropriate software. The FOS is an engineering and design measure employed to ensure the structural integrity of a component or structure. It compares the maximum anticipated load or stresses that the assembly may encounter with its actual capacity to withstand such loads or stress.

The calculation involves dividing the capacity or strength of the assembly by the maximum expected load or stress it is likely to experience. By obtaining a higher factor of safety, we establish a greater margin of safety, thereby reducing the risk of failure or collapse under normal operating conditions or unexpected events. This analysis provides valuable insights into the assembly's ability to handle various loads and stresses, confirming its suitability for its intended purpose. The factor of safety analysis for this assembly is as follows:

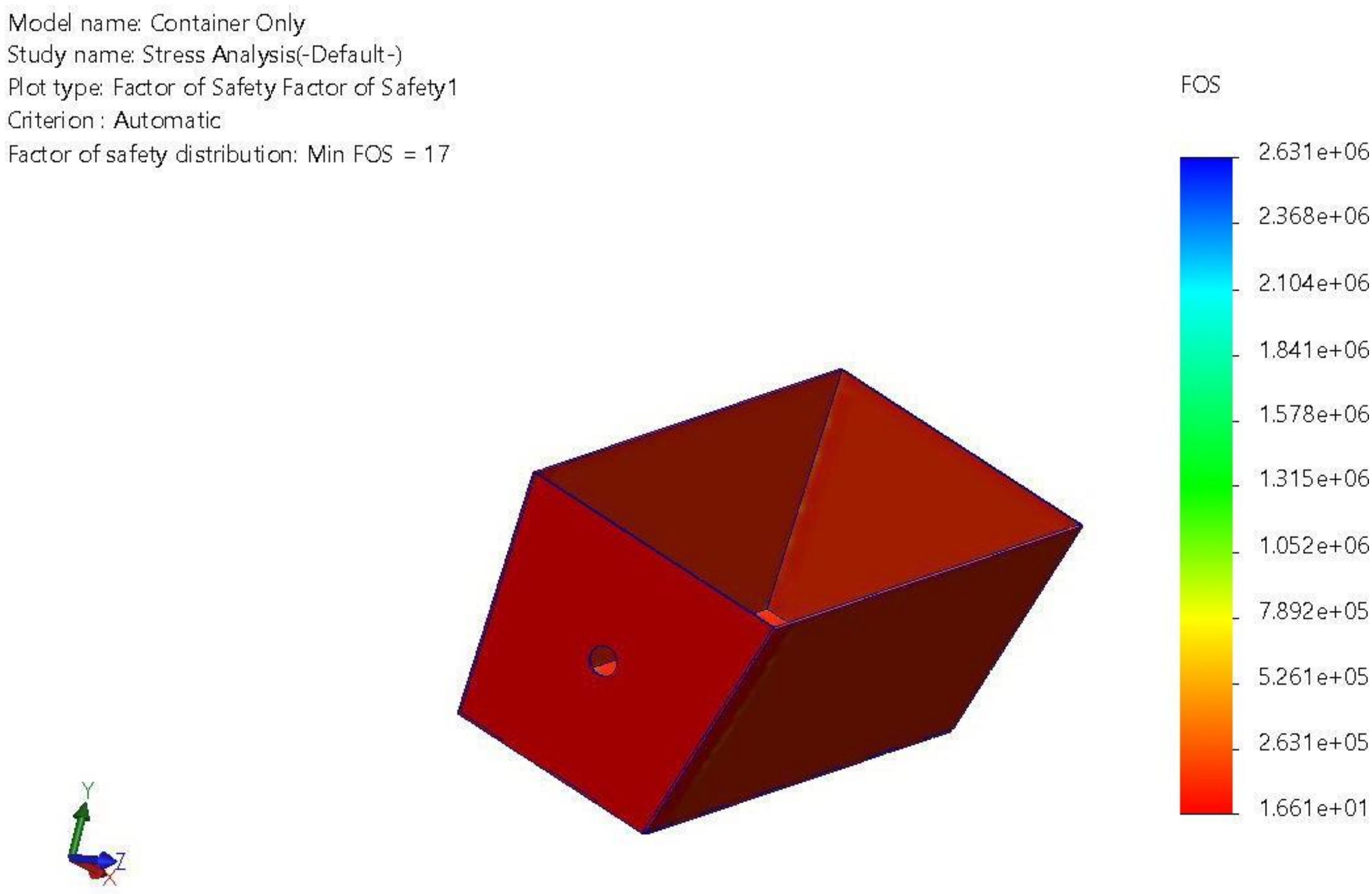


Figure 4-9. Overall, FOS Analysis Plot

According to this analysis, the minimum FOS that is calculated for this assembly is 17. Hence this assembly is more than adequate to house this biogas digester and can support it during it production process.

4.5 Economic Feasibility

Before proceeding with the construction of the proposed biodigester design, it is crucial to evaluate its economic feasibility, which plays a vital role in the system's long-term sustainability. This feasibility breakdown can be divided into the following headings:

4.5.1 Initial Cost Calculation

The design presented in this article suggests the use of a tubular biodigester with a circumference of 4 meters and a length of either 2.1923 or 2.2 meters.

To construct the biodigester, a Plastic HDPE Geomembrane 2mm Sheet is required. As per Shahzad Industries (Local Vendor for the HDPE Geomembrane), The cost per square meter is Rs. 1180. The total dimension of the tubular biogas digester is 8.8 m^2. Hence the cost for the total sheets needed to produce this is Rs 10,384, as per Table 4-8.

Table 4-8. Cost Distribution of Construction of the Tubular Biogas Digester

Ser.	**Cost of HDPE Geomembrane Sheet (Per m^2) (Rs)**	**Total Area of Biogas Digester (m^2)**	**Total Cost of the HDPE Sheets Needed (Rs)**
1.	1180	8.8	10,384

In terms of the inlet and outlet pipe assemblies, uPVC pipes with lengths of 0.8 and 0.4 meters are used, along with a 45 Degree Bend and a Ball valve. As per Master Pipe Industry Ltd, the uPVC pipes with a diameter of 0.1 meters are available with an average length of 13 feet, which is sufficient for our needs. The cost of the pipe is Rs. 1,720, while the 45 Degree uPVC elbow and the ball valve cost Rs. 600 and Rs. 12,000, respectively. Thus, the total cost of the pipe assembly amounts to Rs. 14,320. as per Table 4-9.

Table 4-9. Cost Distribution of the Inlet and Outlet Pipe Assemblies

Ser.	**Cost of uPVC Pipes (Per 13 ft) (Rs)**	**Cost of uPVC Elbow (Per Piece) (Rs)**	**Cost of uPVC Ball Valve (Per Piece) (Rs)**	**Total Cost of the Pipe Assembly (Rs)**
1.	1,720	600	12,000	14,320

To ensure the stability of the trench and provide housing for the biogas digester, a container box made from 5 uPVC sheets is inserted into the excavated trapezoidal trench, as described in previous paragraphs. Each sheet is 0.01 meters thick and can be locally obtained in a size of 2.5 meters by 1.2 meters. For constructing the container box, 4 sheets are sufficient. In the market, a uPVC sheet with a thickness of 0.01 meters costs Rs. 13,500 per sheet, resulting in a total cost of Rs. 54,000 for the container box, as per Table 4-10.

Table 4-10. Cost Distribution of the Container Box Assembly

Ser.	**Cost of uPVC Sheets (Per 2.5m x 1.2 m) (Rs)**	**Number of Sheets Required**	**Total Cost of the Container Box Assembly (Rs)**
1.	13,500	4	54,000

Therefore, the total cost of the proposed system, including the biogas digester, pipe assembly, and container box assembly, amounts to Rs. 78,704, as per Table 4-11.

Table 4-11. Total Cost of the Low Cot Biogas Digester with Container Box Assembly

Ser.	Cost of the HDPE Sheets for the Biogas Digester (Rs)	Cost of the Pipe Assembly (Rs)	Cost of the Container Box Assembly (Rs)	Total Cost of Overall Assembly (Rs)
1.	10,384	14,320	54,000	**78,704**

Comparing these costs to a pre-made biodigester available for sale at Rs. 105,000 from [19], it is evident that our design is more economical and sustainable. Although the vendor's biodigester offers a larger size, higher output, and total biodigester volume compared to the one proposed in this article, our design presents advantages in terms of compactness and installation integrity. The proposed design is housed within a trench, saving unnecessary space, while the vendor's product is enclosed in a shed-like structure. Additionally, the smaller size and weight of our design make it highly portable, and it can be easily assembled by a first-time installer, eliminating the need for certified professionals for installation. Further clarity about its feasibility can be achieved via the Discounted Cash Flow (DCF) approach.

4.5.2 Introduction to Discounted Cash Flow (DCF) Approach

The economic analysis conducted in this study is grounded in the rigorous discounted cash flow (DCF) approach [20]. By employing this established methodology, the study explores the projected future cash flows and evaluates them by discounting them at a rate that accurately represents the cost of capital. Through this comprehensive analysis, the study aims to derive essential financial indicators, such as the discounted payback period (DPP) , the net present value (NPV), internal rate of return (IRR) and return on investment (ROI) [20][21][22].

NPV: The Net Present Value (NPV) is a widely used financial metric that helps evaluate the profitability and viability of an investment or project [21][22]. It calculates the present value of expected cash inflows and outflows by considering the time value of money. By discounting future cash flows using an appropriate discount rate, NPV provides insight into whether an investment will generate positive or negative returns [22]. A positive NPV suggests potential profitability, while a negative NPV indicates potential financial loss

[21][22]. NPV is a valuable tool for decision-making, as it considers the entire cash flow profile and assists in comparing different investment options. It can be denoted with the following formula:

$$\text{NPV} = -I + \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{23}$$

Here, I represents the initial cost, CF is the cash flow, r is the discount rate and t is the project lifetime.

IRR: The Internal Rate of Return (IRR) is a key financial metric used to assess the profitability of an investment. It represents the discount rate at which the net present value (NPV) of cash flows equals zero [22]. By calculating the IRR, decision-makers can determine the rate of return at which an investment break even. If the IRR exceeds the required rate of return, it indicates that the investment is potentially profitable [21][22]. The IRR provides a concise measure of an investment's attractiveness and assists in decision-making by evaluating its internal profitability. Equation (23) can be altered as follows:

$$0 = -I + \sum_{t=0}^{N} \frac{CF_t}{(1+IRR)^t} \tag{24}$$

Here, I represents the initial cost, CF_t is the cash flow, r is the discount rate and t is the project lifetime.

DPP: The Discounted Payback Period (DPP) is a financial metric used to determine the time it takes for an investment to recover its initial cost in present value terms [20]. Unlike the traditional payback period, which only considers undiscounted cash flows, the discounted payback period considers the time value of money by incorporating discounted cash flows [20]. By discounting the cash flows using an appropriate discount rate, the metric provides a more accurate measure of the investment's recovery timeline. A shorter discounted payback period indicates a quicker recovery of the investment's initial cost, taking into consideration the present value of cash flows [20]. It can be denoted with the following formula:

$$DPP = \frac{ln\left(\frac{1}{\left(1-\left(\frac{(I \times r)}{CF}\right)\right)}\right)}{ln(1+r)} \quad (25)$$

Here, I represents the initial cost, CF is the cash flow and r is the discount rate.

ROI: Return on Investment (ROI) is a widely used financial metric that measures the profitability and efficiency of an investment. It represents the ratio of the net profit generated from an investment to the initial cost of that investment, expressed as a percentage [22]. By calculating ROI, investors can evaluate the effectiveness of their capital allocation and assess the returns generated relative to the investment's cost. A higher ROI indicates a more favorable investment outcome, while a lower ROI suggests a less efficient use of capital [22]. ROI is a valuable tool for comparing and prioritizing different investment opportunities based on their potential returns. It can be denoted with the following formula:

$$ROI = \frac{Net\ Profit}{I} \times 100 \quad (26)$$

Here, I represents the initial cost.

4.5.3 Discounted Cash Flow (DCF) Calculations

To obtain a comprehensive understanding of the feasibility of an investment or project, it is crucial to calculate the key elements within the Discounted Cash Flow (DCF) approach. These elements play a vital role in assessing the financial viability and potential returns of the investment. In the following section, we will perform the necessary calculations using the values provided in the accompanying table.

The values required for these calculations are given in the following table:

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Table 4-12. Required Values for DCF Calculations

Ser.	Theoretical Biogas Production (m^3/day)	Theoretical Biogas Production (m^3/year)	LPG Equivalent Value (Kg)	Annual Income/ Savings (Rs)	Initial Cost (Rs)	Project Lifetime (year)	Discount Rate (%)
1.	0.43	154.8	66.564	12,552.78	78,704	10	8

The Theoretical Biogas Production (TBP_y) per year can be calculated from the per day value as follows:

$$TBP_y = 0.43 \times 30 \times 12 = 154.8 \text{ m}^3 / \text{year} \tag{27}$$

The LPG equivalent value (LPG_{EV}) of biogas is a measure used to compare the energy content or heating value of biogas with Liquefied Petroleum Gas (LPG), a commonly used commercial fuel [20]. By understanding and comparing the energy potential of biogas in relation to LPG, we can assess the value and potential benefits of using biogas as a fuel source. This value is particularly relevant when calculating the potential cash flows associated with the production and utilization of biogas through a tubular biogas digester. It helps quantify the economic impact and financial viability of implementing biogas projects by estimating the energy equivalence to a widely recognized commercial fuel like LPG. 0.43 kg LPG is equivalent to 1 m3 of biogas [20]. Hence:

$$LPG_{EV} = 0.43 \times 154.8 = 66.564 \text{ kg} \tag{28}$$

Rate of LPG in Pakistan, as of 01 July 2023 is Rs 2,092.12 / 12 kg cylinder [23]. Hence:

$$\text{Number of cylinders of LPG} = \frac{66.564}{12} = 5.547 \sim 6 \tag{29}$$

$$\text{Annual Income} = 6 \times 2092.12 = \text{Rs } 12{,}552.72 \tag{30}$$

The Project Lifetime has been set for 10 years, as it is the average life span of a particular biogas digester. The discount rate has been set at 8% [20]. Finally, the calculated values of the NPV, IRR, ROI and DPP are given in the following table:

Table 4-13. Calculated DCF Element Values

Ser.	**NPV (Rs)**	**IRR (%)**	**ROI (%)**	**DPP (years)**
1.	**5,526.18**	**9.5**	**15.95**	**9.05**

4.5.4 Final Verdict

According to the data calculated for the project, as per the values shown in Table 4-13, it is evident that the project is not only worth pursuing but also financially feasible.

One key indicator is the positive Net Present Value (NPV) of Rs 5,526.18. NPV considers the time value of money by discounting future cash flows back to the present at a specified rate. In this case, with a discount rate of 8%, the positive NPV signifies that the expected cash inflows from the project exceed the initial investment cost. This suggests that the project has the potential to generate more value than the amount of capital invested, thus indicating its feasibility.

Another important indicator is the Return on Investment (ROI) of 15.95%. The ROI measures the profitability of a project relative to its cost. In this scenario, the ROI of 15.95% implies that for every unit of currency invested in the tubular biogas digester project, a return of 15.95% can be expected. A higher ROI suggests better profitability and further supports the feasibility of the project.

The Discounted Payback Period (DPP) is another indicator that supports the feasibility of your project. The DPP of 9.05 years represents the time required for the cumulative discounted cash inflows from the project to equal or exceed the initial investment. By incorporating the discount rate, the DPP accounts for the time value of money. In this case, with a DPP of 9.05 years, the project is expected to recover the initial investment within its 10-year lifetime. This implies that the project has the potential to generate positive cash flows beyond the recovery period, further bolstering its feasibility.

Furthermore, the Internal Rate of Return (IRR) of 9.5% plays a significant role in determining the feasibility of the project. The IRR is the discount rate that equates the present value of cash inflows with the present value of cash outflows. In this case, with an IRR of 9.5% that exceeds the discount rate of 8%, the project is expected to deliver a return greater than the required rate of return. This suggests that the project is financially feasible and has the potential to generate positive returns.

4.6 Discussion

The integration of biogas technology serves as a crucial element in delivering clean energy solutions to rural communities and urban households, particularly in developing nations. To effectively promote and adopt this technology, it is essential to design biogas digesters that cater to the specific requirements of users, thereby instilling confidence and trust in the efficacy of the technology. This necessitates a meticulous consideration of the physical and process parameters underlying the digester design to ensure optimal performance.

One pivotal aspect of the physical parameters involves the design of the inlet and outlet systems of the biogas digester. For the construction of these components, it is recommended to employ polyvinyl chloride (PVC) pipes with a diameter ranging from 90 to 100 mm. The inlet pipes should possess a length of 60 to 100 cm, while the outlet pipes should be slightly longer, typically by approximately 20 to 50 cm. These dimensions are carefully chosen to facilitate a smooth and efficient flow of materials within the digester, thereby promoting an effective biogas production process.

Furthermore, careful planning is essential when designing the biogas convey pipeline responsible for transporting the produced biogas from the digester to its designated consumption point, such as the kitchen. To ensure safety and enable convenient maintenance activities, the incorporation of two stop corks is advisable—one located at the digester tank and another at the biogas consumption point. These stop corks act as safety measures, allowing for the isolation of different sections of the pipeline for maintenance purposes. Additionally, the inclusion of a pressure release valve in the biogas convey pipeline proves beneficial in regulating the pressure within the storage tank. This valve facilitates controlled release of biogas if the pressure exceeds optimal levels, thereby safeguarding the integrity of the system.

To optimize the performance of the biogas digester, a comprehensive analysis of the feedstock used is imperative. This analysis helps ascertain the percentage of total solids (%TS) and volatile solids (%VS) present within the feedstock. These parameters play a vital role in determining the organic loading rate (OLR), which specifies the quantity of feedstock that can be efficiently processed by the digester. The accurate design of the OLR ensures efficient biogas production and promotes overall stability of the system.

By attentively considering these critical design factors, which include the physical parameters of the digesters, and conducting an in-depth analysis of the feedstock, biogas technology can be effectively tailored to meet the specific energy needs of diverse communities, regardless of whether they are situated in rural or urban settings. This approach contributes significantly to a cleaner and more sustainable energy future, empowering communities with a reliable and eco-friendly energy source.

4.7 Future Recommendations:

This research is quasi-complete and can stand as a relevant source. Yet future studies and research can be done to better amplify and solidify the stronghold of Biogas Digesters in Pakistan. Some of these are as follows:

4.7.1 Use of CFD in Biogas Digester Design

In this research, the design of the tubular biogas digester and the subsequent container box design using external parameters from that design are conducted by integrating the numerical iteration method from the Martin Herrero article. While this method yields more accurate results compared to the initial idealistic design approach, it still fails to accurately predict the actual changes occurring within the tubular biogas digester. To overcome this limitation, the integration of Computational Fluid Dynamics (CFD) analysis in the design methodology can provide more detailed insights. Some potential applications of CFD analysis in biogas digester design include:

Energy Transfer during Phase Change: CFD can simulate and analyze the energy transfer processes that occur during the phase change phenomena within the digester, such as the conversion of organic waste into biogas.

Energy and Heat Transfer due to Slurry Flow: By modeling the flow of the slurry within the digester, CFD analysis can predict energy and heat transfer characteristics, helping optimize the design for efficient biogas production.

Mass Transfer: CFD simulations can provide valuable information about the mass transfer phenomena taking place during the digestion process, aiding in the understanding and improvement of biogas production efficiency.

Flowrate Optimization: CFD analysis can accurately determine the exact flow rates of the inlet reactants and outlet products, allowing for better control and optimization of the overall biogas production process.

Pipe Linkage Optimization: (CFD) analysis can be used to design efficient biogas digester linkage systems by optimizing the pipe system layout, insulation, and routing to minimize losses.

4.7.2 Different Case Studies and Biogas Digester Capacities

While the tubular biogas digester design presented in this research is suitable for small households, further studies can explore the integration of larger and more diverse biogas digester systems for larger households or commercial installations. Conducting different case studies can provide insights into the scalability, adaptability, and performance of biogas digesters in various settings, enabling the identification of optimized designs for different applications.

4.7.3 Updated Regulatory Policies for Biogas Digesters

Although the Government of Pakistan (GoP) has taken initiatives to promote biogas technologies, there is a need for an integrated and comprehensive approach. The Alternative Renewable Energy (ARE) Policy 2019 sets clear targets for renewable energy generation, including waste-to-energy and biogas, but a cohesive action plan is required to achieve these targets. The existing Integrated Generation Capacity Expansion Plan (IGCEP) 2021 does not include commercial-scale biogas plants in the generation mix by 2030. Therefore, a further study into developing an integrated action plan that incorporates all relevant initiatives aligns with the ARE policy and includes specific provisions for promoting biogas digesters is essential to drive the growth of the biogas sector in Pakistan.

4.7.4 Optimizing the Biogas Digester-Household Linkage Network

A significant portion of losses and inefficiencies in the overall biogas system can occur in the pipe linkage system connecting the biogas digester to the household end usage point. Further study in this domain can focus on optimizing the pipe linkage system and minimizing losses through improved pipe design, insulation, and routing strategies. Additionally, determining the optimum distance from the biogas digester to the end user point, and optimizing the placement and number of complementary accessories such as valves and pumps, can further enhance the overall efficiency and performance of the biogas system.

4.7.5 Training Programs for Professionals

To increase the number of skilled professionals in the field of biogas digester installation and maintenance, a comprehensive training program can be developed. Further Study into the development of this program should be done. This program should cover theoretical knowledge about biogas digester design principles, construction techniques, operation, and maintenance procedures. Practical training should include hands-on experience in biogas system installation, troubleshooting, and safety protocols. The program can be implemented through collaboration between government institutions and non-governmental organizations.

Summary

Here, an analysis of the container box model's structural performance is seen, focusing on stress and factor of safety calculations. The material selected for the container box was "PVC Rigid," which possesses specific properties suitable for the container box. The file provides insights into the efficiency of the system in converting organic waste into biogas and highlights the significance of biogas quality and biodegradation rate as performance parameters of a biogas digester system. The stress diagram reveals that the assembly experiences varying stress levels, ranging from 12.67 to 3.4393 x 10^6 N/m^2, and the assembly remains intact under the current force and pressure exerted. The study concludes that the strength and durability of the assembly are more than sufficient to withstand the operational demands imposed by the biogas digester. In the end, the economic feasibility analysis also indicates that this setup is cheaper, easy to install, and overall feasible for small household use in Pakistan.

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Chapter 5: Conclusion

To address Pakistan's energy crisis, the Indigenous Low-Cost Tubular Biogas Digester with Portable Container Box emerges as a promising solution. This paper has delved into a thorough examination of the root causes and repercussions of the crisis, in addition to providing an in-depth analysis of the design and functionality of the biogas digester system. Notably, the design process incorporates an advanced mathematical methodology, ensuring utmost precision and reliability in the system's performance. Moreover, the system's efficacy has been confirmed through rigorous experimental studies.

While the implementation of this system in Pakistan may encounter certain challenges, such as limited awareness and funding, they are not insurmountable. By prioritizing education and raising awareness about the benefits and practicality of biogas technology, these challenges can be effectively addressed. Furthermore, government support through funding schemes and favorable policies can play a pivotal role in facilitating the widespread adoption of such sustainable energy solutions.

The Indigenous Low-Cost Tubular Biogas Digester with Portable Container Box offers a myriad of advantages for Pakistan. Firstly, it presents a sustainable approach to addressing the country's energy needs, relying on locally available resources, such as organic waste and agricultural byproducts. This not only reduces dependency on traditional fossil fuels but also offers a reliable and renewable energy source that can contribute to long-term energy security.

Furthermore, the low-cost nature of the digester system makes it particularly beneficial for small households and communities with limited financial resources. By utilizing affordable materials and incorporating cost-effective designs, this biogas digester offers an accessible solution that can improve the quality of life for many individuals, particularly in rural areas.

Another crucial aspect to highlight is the positive environmental impact of this technology. The utilization of organic waste in the biogas production process helps mitigate the release of harmful greenhouse gases, thereby reducing the overall carbon footprint. Additionally, the resulting organic fertilizer, known as digestate, serves as a valuable byproduct that can be used to enhance agricultural practices, promoting sustainable and eco-friendly farming techniques.

In conclusion, the Indigenous Low-Cost Tubular Biogas Digester with Portable Container Box holds significant promise as a viable solution to Pakistan's energy crisis. With its well-defined design methodology, validated performance, and potential for widespread implementation, this system offers a sustainable and cost-effective approach to meet the country's energy needs. By addressing challenges through education and governmental support, Pakistan can embrace this technology, benefiting households, reducing environmental impact, and making substantial strides towards a more sustainable and energy-secure future.

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Appendix 1 – Publications

Design of Indigenous Small Scale Low-Cost Tubular Biogas Digester with Portable Container Box

Muhammad Ajdar Aneeq Malik [a], Rabia Liaquat [a], Adeel Waqas Ahmed [a], Nadia Shahzad [a], Majid Ali [a],*

Abstract:

This research study proposes an Indigenous Small Scale Low-Cost Tubular Biogas Digester with a Portable Container Box to address Pakistan's energy crisis, particularly for small households. The compact digester is designed to meet the energy needs of small rural households, distinguishing it from larger models. Housed within a portable container box, installed in the ground for convenient placement, this solution prioritizes portability, protection, and ease of installation. The research focuses on refining the design parameters through a meticulous numerical iteration process, ensuring accuracy and bridging the gap between simulations and real-life outcomes. The container box undergoes rigorous analysis, considering durability, strength, and cost-effectiveness. By integrating the refined parameters, the container box is confirmed to provide a secure and efficient housing solution, meeting requirements for easy assembly, disassembly, protection, and portability. This research presents an innovative and tailored approach to Pakistan's energy crisis, benefiting small households with a compact and aesthetically pleasing solution.

Keywords: Tubular Biogas Digester, Indigenous, Pakistan, Portable, Mathematical Iteration Modeling, Protective Container Box, Trench Optimization

Journal: **Agricultural Research**

Impact Factor: **1.55**

Status: **Under Review**