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Economic and Environmental Impact Assessment of Biogas Energy and Development of a User-Friendly Biogas Capacities Calculator

by

Muhammad Tanveer

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In humble reverence and unwavering devotion, I dedicate the entirety of this thesis to Allah Almighty, seeking His divine guidance as I embark on this scholarly journey

CERTIFICATE OF APPROVAL

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Muhammad Tanveer

(MEM231004)

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Dr. Afshan Naseem	NUST, Islamabad
(b)	Internal Examiner	Dr. Shummaila Raseed	CUST, Islamabad
(c)	Supervisor	Dr. Ghulam Asghar	CUST, Islamabad

Dr. Ghulam Asghar
Thesis Supervisor
July, 2025

Dr. Muhammad Mahabat Khan
Head
Department of Mechanical Engineering
July, 2025

Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
July, 2025

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I am dedicating this thesis to Allah Almighty, whose boundless mercy and infinite wisdom have guided me through every step of this journey. His grace has been my strength, and His blessings have made this achievement possible. I also extend my heartfelt reverence to Prophet Muhammad (PBUH), the Divine Servant Leader, whose teachings have profoundly influenced my life and instilled in me the values of perseverance, integrity, and compassion.

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(Muhammad Tanveer)

Abstract

Biogas presents a sustainable and economically viable solution for energy generation, waste management, and environmental conservation. This thesis emerge estimation of Biogas Production Potential and Greenhouse Gas Emissions Reduction for sustainable energy management using biogas estimation model with the help of Microsoft Excel. Animal waste from four categories provides a viable opportunity to reduce dependence on fossil fuels while addressing the growing energy needs of Pakistan. Biogas technology is recognized as an effective solution for mitigating climate change while supplying a renewable energy source, particularly in Punjab. The research relies on livestock population data from the Pakistan Bureau of Statistics and the Ministry of Livestock & Dairy Development for the years 2013-2023. The study estimates manure production, biogas production capacity, electricity potential, GHG reduction, and bio-fertilizer output for Punjab in 2023. The findings indicate that livestock waste amounted to 573.24 million tons per year, which could generate approximately 8.63×10^4 million m^3/year of biogas. This biogas potential translates into 87.88 TWh/year of electricity annually, meeting nearly 70% of Pakistan's total electricity consumption. Moreover, replacing conventional fuels with biogas could result in an annual GHG reduction of 271.95 million tons of CO_2. Furthermore, an estimated 36.10 million tons/year of bio-fertilizer could be produced, offering an environmentally friendly alternative to synthetic fertilizers and enhancing soil fertility. The prediction/forecasting concluded on the year 2030 that livestock waste amounted, biogas production, electricity generation, bio-fertilizer and GHG emission reduction to 1810 million tons/year, 2.82×10^5 million m^3/year, 286 TWh/year, 113.91 million tons/year and 891.1 million tons/year of CO_2 respectively. The study underscores the immense potential of biogas technology in meeting energy demands while promoting environmental sustainability. The adoption of biogas can significantly reduce reliance on fossil fuels, lower carbon emissions, and support agricultural productivity. However, realizing this potential requires strategic investments, policy interventions, and financial incentives to facilitate widespread biogas adoption. By integrating biogas into Pakistan's energy framework, a sustainable and economically viable solution can be achieved, ensuring long-term benefits for energy security and climate change mitigation.

Keywords: Biogas, renewable, electricity generation, animals waste, bio-fertilizer, GHG emission reduction, sustainability, waste to energy.

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Abbreviations

AD	Anaerobic Digestion
BFY	Bio-Fertilizer Yield
Bp	Biogas Production
CHG	Green House Gas
CHP	Combined Heat & Power
CRi	Collective Ratio
Cat-I	Category-I (Buffalo & Cow)
Cat-II	Category-II (Sheep & Goat)
Cat-III	Category-III (Camel, Donkey & Horses)
Cat-IV	Category-IV (Chickens)
DM	Dry Mass
GWP	Global warming Potential
ICE	Internal Combustion Engine
LCVm	Lower Calorific Value of Methane
MOTE	Million Tons Of Oil Equivalent
NAi	Number of animals
NDCs	Nationally Determined Contributions
NPK	Nitrogen, Phosphorus, and Potassium
OLRs	Organic Loading Rates
PPP	Public Private Partnership
QE	Electricity Generation
ROI	Return on Investment
SDGs	Sustainable Development Goals
SMYi	Specific Methane Yield of Manure For Animal

TCM	Total Collectable manure
TS	Total Solid
TWh	Tera Watt Hour
UMPi	Unit manure Potential
VS	Volatile solids

Chapter 1

Introduction

1.1 Background

As a growing alternative to conventional energy fuels, biogas facilities are being developed to harness methane gas produced by bacteria through anaerobic digestion of animal waste and other organic materials. The end product, primarily natural gas, can be utilized in the same applications as conventional fuels.

It has long been known that organic matter when left to it will undergo changes and decomposition. Researchers are trying to explore this process since several years, sometimes with the aim of slowing it down, as in food preservation experiments and sometimes for speeding it up, as in sewage disposal research. It was found that the decomposition process is the work of microparticles which feed on raw material and which yield by-products. Some microorganisms prefer cold conditions, others thrive in heat, some need oxygen while others require its absence, some want light, others want dark, each has its own preference for moist or dry conditions. Their by-products may be any combination of solid, liquid or gaseous matter. The decomposition of organic waste can result in the formation of different grades of combustible gas. Marsh gas, created by the decay of dead plants in the swamps is explosive in certain concentrations. Septic tanks are often provided with a vent to allow for the escape of combustible gases formed inside. The substantial amounts of gas would be advantage to try to collect and use it for fuel. Early efforts, this direction were found in municipal sewage treatment plants, where the efficient production and collection of gas, released by the bacteria acting on the waste materials, became as important an objective as the neutralization of those wastes. The use of biogas in first time was heating of water for bath in Assyria during 10th century BC. In the 17^{th} century it was recognized that combustible gasses could be produced when the organic material decomposes. and there is direct relationship between burning of organic material and gas produced. According to Humphrey Davy found out in 1808 that animals dung produce methan [1]. In the latter half of the 20th century, biogas technology became increasingly applied in industrial and urban waste treatment, as well as energy conservation. However, its adoption in rural areas remained limited. By the end of 1988, China had reported only 4.7 million domestic biogas digesters [2]. The rapid expansion of biogas usage in several Asian, African, and Latin American countries occurred during the 1970s and the early 1980s. In China's Guangdong province, biogas was adopted at a commercial level. In 1921, a biogas tank utilizing domestic waste was constructed [3]. The first biogas unit in Pakistan was installed in Sindh in 1959. Since then, numerous biogas plants have been established across the country [4]. The Pakistan government recognized the potential of biogas as an alternative energy source in 1974, prioritizing its development to address energy shortages and promote sustainable energy solutions. This initiative aimed to reduce reliance on fossil fuels, improve waste management, and enhance rural energy access [5]. The Pakistan Renewable Council for Appropriate Technology established 21 biogas plants using Chinese technology. However, these plants failed due to structural leaks. Subsequently, the Indian biogas design was adopted, and ten demonstration plants were installed in Azad Jammu and Kashmir. The performance of the Indian-designed plants was satisfactory, leading to their adoption for mass deployment [6]. In 2002, approximately 3.4 million small-scale biogas plants were installed in India. This widespread adoption was driven by government incentives, promoting biogas as a reliable renewable energy source. These plants utilized local organic waste, helping to meet rural energy needs, reduce environmental pollution, and improve waste management practices. The success of this initiative set a model for other countries seeking sustainable energy solutions [7].

1.2 Problem Statement

The increasing energy demands and environmental concerns in Pakistan necessitate the exploration of sustainable and renewable energy sources. Animal manure, a widely available organic resource, presents a significant opportunity for biogas production, which can serve as an alternative fuel source for meeting daily energy needs. However, there is a lack of comprehensive data and analysis on the biogas potential of animal manure across different regions of Pakistan, including its feasibility for electricity generation, economic viability, and environmental benefits. These study objectives to address this gap by evaluating the biogas potential of animal manure from various livestock (cattle, sheep, goats, horses/mules/donkeys, and chickens) across 8 Divisions and 81 cities in Pakistan. It assesses the feasibility of both small-scale household biogas systems and large-scale community biogas plants, considering local conditions, resource availability, and socio-economic factors. Additionally, the study calculates the electricity generation potential, CO_2 emission reductions, bio-fertilizer as by-product and installation costs of biogas plants in regions with the greatest biogas potential.

1.3 Research Question

The research questions are mentioned below for this study which is divided into economic viability, feasibility and technical aspects, environmental and social impact, forecasting aspects.

1. What is the situation/amount of substrates available to produce biogas?
2. What methodologies can be developed to accurately measure and quantify the actual methane emissions from biogas systems?
3. What is the collective environmental impact (in terms of GHG emissions and overall carbon footprint) of combining manure management, biogas production, electricity generation, and bio-fertilizer application in Pakistan?

4. How does biogas compare to solar energy in terms of efficiency, cost-effectiveness, and environmental benefits within the context of Pakistan's energy landscape?
5. What predictive trends for biogas potential and associated GHG emissions are anticipated in Pakistan up to 2030, and what factors will drive these changes?
6. How can a user-friendly tool be designed and implemented to calculate biogas potential, supporting stakeholders in decision-making processes?

1.4 Study Objectives

The purpose of the Punjab region's biogas production feasibility study is to assess the viability and possible advantages of introducing biogas technology in the area. To determine the potential for producing biogas in accordance with the need for energy and the data is examined. The following points provide a summary of the research work's main goal:

1. To ascertain the quantity and accessibility of cattle substrates appropriate for the production of biogas
2. Establish and validate reliable methodologies to accurately quantify methane emissions from biogas systems.
3. Integrate data from manure management, biogas production, electricity generation, and bio-fertilizer application to assess the collective GHG emissions and carbon footprint.
4. Compare biogas with solar energy by evaluating their efficiency, cost-effectiveness, and environmental benefits.
5. Develop a predictive model to forecast biogas potential and associated GHG emissions in Pakistan up to 2030.

6. Design and implement a user-friendly biogas capacity calculator to support strategic decision-making by stakeholders.

1.5 Significance of Study

The study on the economic and feasibility analysis of biogas plants in Pakistan is significant for addressing the country's energy, environmental, and socio-economic challenges. Pakistan faces frequent power shortages and heavy reliance on imported fossil fuels, making biogas plants a viable decentralized and renewable energy solution. By converting organic waste into energy, biogas technology reduces energy costs, generates income through bio fertilizers, and enhances energy security. Environmentally, it lowers greenhouse gas emissions, promotes sustainable waste management, and reduces pollution. For rural communities, biogas plants provide clean energy, foster economic growth, and improve living standards, aligning with Pakistan's sustainable development goals. The study offers evidence-based policy recommendations to support biogas adoption, including incentives and regulatory frameworks. Its findings can guide scaling up biogas technology in Pakistan and other developing countries which participate energy and environmental sustainability.

1.6 Thesis Organization

The complete research roadmap is outlined sequentially, providing a brief overview of each chapter as follows.

- **Chapter 1** This chapter provides an outline of the research, covering the background, problem statement, research questions, objectives, significance, and supporting theories.
- **Chapter 2** This chapter reviews the existing literature on the topic, encompassing previous research, scholarly articles, journals, books, and annual reports. All of the related material of biogas production, electricity generation,

bio fertilizer and GHG emission in an organization defined in this section properly. This chapter highlights various theories relevant to the research, providing a comprehensive review of past studies related to the thesis topic.

- **Chapter 3** The research methodology outlines the systematic approach used to conduct the study, including data collection, calculations and analysis methods. The study is based on four major livestock categories Category-I for Cattle and Buffalo, Category-II for Sheep and Goat, Category-III for Camels, Horses, and Donkeys, Category-IV for Poultry. Quantitative analysis is employed to process and interpret numerical data, ensuring accuracy in biogas production, electricity generation, bio-fertilizer estimation, and GHG emission reduction. Moreover, a comparative analysis of biogas and solar energy is conducted to assess their efficiency.

- **Chapter 4** The Results and Discussion chapter analyzes biogas production, electricity generation, bio-fertilizer estimation, and GHG reduction across livestock categories. It compares biogas with petrol, highlighting its efficiency, sustainability, and environmental benefits in reducing carbon footprints.

- **Chapter 5** This chapter examines manure, biogas, electricity, bio-fertilizer, and GHG emissions from 2013 to 2023, with forecasts for 2024 to 2030 using third-order polynomial regression, emphasizing growth trends, renewable energy expansion, and sustainability-driven policies.

- **Chapter 6** In this chapter, the conclusion is drawn on the basis of detailed analysis. The discussion is transparent and sufficient to define the complete view of research study. The recommendations of the study are documented along with the future direction.

Chapter 2

Literature Review

This literature review focuses on past academic research papers, offering new arguments and insights into the topic. The review is organized into four sections, each discussing different aspects of prior studies. The first section examines the potential of animal waste as a valuable resource, emphasizing its conversion into biogas. Building on this, the second section consists on the generation of electricity from biogas. The third section highlights minimize the GHG emission accumulated by use of biogas. Finally, in fourth section delves into bio-fertilizers, specifically the by-products of biogas residues, and their applications in agriculture. Each section is supported by relevant research findings, providing a comprehensive understanding of the subject.

2.1 Biogas Production

Renewable energy is becoming increasingly popular globally as concerns grow over the potential depletion of fossil fuel reserves. This has spurred scientists and engineers to search for reliable and sustainable alternatives to meet the world's energy demands. Among these alternatives, biomass stands out as a viable option. Biomass refers to animal waste that can be converted into energy. It is considered renewable because it relies on materials that are continuously produced in nature [7].

The potential for biogas technology in the region, focusing on its economic and environmental benefits. Using spatial analysis, the study identifies areas with the high biogas potential, based on livestock density and organic waste availability. It finds that biogas offers a cost-effective alternative to traditional fuels, reducing household energy costs and promoting environmental sustainability. Biogas contributes to climate resilience by lowering carbon emissions, reducing deforestation, and improving soil fertility through organic fertilizers. Despite these benefits, challenges such as high setup costs and limited awareness hinder widespread adoption. The paper calls for government intervention in the form of subsidies, infrastructure development, and training programs to growth and environmental protection in southern Khyber Pakhtunkhwa [8].

The biogas potential as a sustainable energy solution to tackle Pakistan's escalating energy crisis. As the country faces dwindling conventional energy resources, rising fuel costs, and environmental challenges, the study position biogas as a viable alternative, especially for rural communities. The paper highlights that biogas can minimize the fossil fuels which mean lower energy price and help GHG emission. Moreover, the organic by-products generated from biogas can serve as fertilizers, boosting agricultural productivity. However, the study identifies several obstacles to widespread biogas adoption, including high upfront costs, limited awareness, and in adequate government support. To address these challenges, the paper calls for policies that include financial incentives, subsidies, and public awareness initiatives [9].

How biogas offers a cost-effective and sustainable energy alternative, reducing reliance on conventional energy sources like firewood and Kerosene. Key factors that drive adoption include the availability of livestock, awareness of environmental benefits, and the costs of installation. Biogas from anaerobic digestion offers a renewable energy option but requires upgrading to remove impurities and boost calorific value. A review of technologies like cryogenic separation, membranes, adsorption, and scrubbing highlights chemical scrubbing as the most effective and cost-efficient method for producing high-purity methane [10].

Biogas production follows a closed nitrogen and carbon cycle that begins with feedstock production and concludes with digestate utilization as fertilizer. During photosynthesis, plant absorbs CO_2. Animals consume plants, therefore a significant portion of the carbon absorbed ends up in manure. If plants, such as trees, are not consumed, they may be burned, producing CO_2, or converted into organic matter at the end of their life cycle. If sufficient trees are planted, it will take another 20 to 50 years for carbon to be eliminated from the atmosphere by plant combustion.

It is important to take into account that CO_2 is also produced by the respiration of plants and animals along the entire cycle of matter. Biogas is created and can be stored if the organic matter and manure that are produced are utilized in the anaerobic digestion process. Heat and power are produced when biogas is burned. Exhaust gases such as CO_2 and water are additional products. The carbon cycle is finished when the plants choose the CO_2 that has been released into the atmosphere for photosynthesis. A portion of the carbon molecules that are still present in the digestate are utilized as fertilizers to raise the soil's carbon content. Figure 2.1, is essential to comprehending biogas.

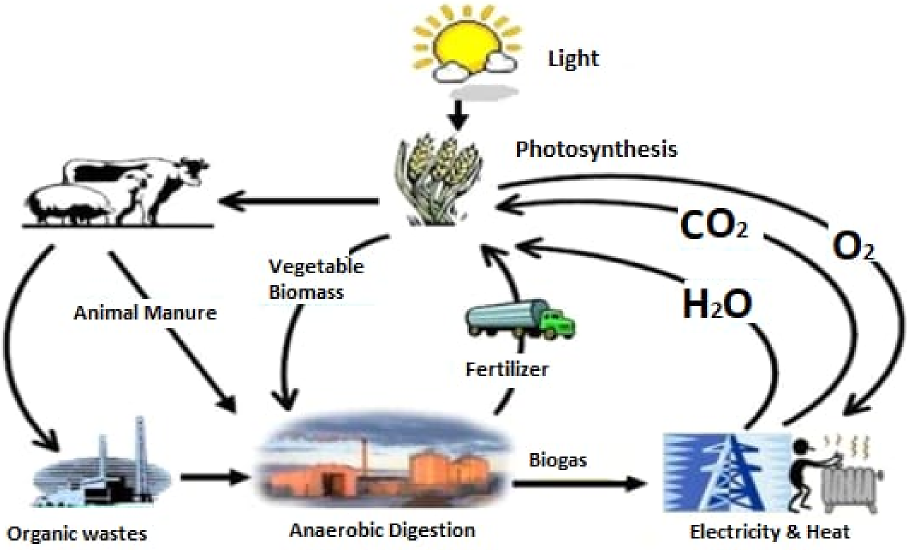


FIGURE 2.1: Cycle of matter

Anaerobic digestion (AD) which method to manage the animal or solid waste. Through bibliometric tools, the study analyzes publications, citations, and global collaboration to map out key trends, leading contributors, and emerging topics in this field, the analyses shows that anaerobic digestion has become a prominent focus due to it environmentally friendly and sustainable approach to waste treatment, biogas production, and renewable energy generation. The study highlights the countries, institutions, and researchers at the forefront of AD research, tracing the growth of scientific output over the years. A study in South Korea developed a predictive model to estimate biogas yields from anaerobic co-digestion of various organic wastes, incorporating theoretical biogas potential and biodegradation rates based on mixing ratios. Model performance was validated using data from 20 operational Co-AD plants, showing strong statistical significance and acceptable predictive accuracy (R^2 and RMSE). [11].

Anaerobic digestion is a sustainable biological process that converts organic waste into useable resources like energy and nutrients. This process occurs in an oxygen-free environment, allowing microorganisms to break down complex organic substances efficiently. The energy recovered during anaerobic digestion is generally in the form of biogas, a renewable energy source made up primarily of methane and carbon dioxide that can be used to generate power, heat homes, or fuel. A study explored integrating biomass-derived syngas and geothermal trigeneration into a methane-fueled Brayton cycle to boost energy efficiency and sustainability.

Using EES modeling, energy, energy, and economic analyses showed significant gains in power and freshwater output, with multi-objective optimization revealing energy efficiencies up to 29.52% and attractive payback periods [12].

2.1.1 Hydrolysis

Carbohydrates, lipids, and proteins are the three primary macronutrients in organic matter, and they undergo distinct biochemical transformations during the initial stages of decomposition. Carbohydrates, which include starches, cellulose, and other polysaccharides, are broken down into simple sugars such as glucose, fructose, and galactose through enzymatic reactions. This process, often catalyzed by enzymes like amylase or cellulase, makes these sugars soluble and more accessible for further microbial degradation. Similarly, lipids, which are fats and oils, are transformed into glycerol and fatty acids through a process known as lipolysis, catalyzed by lipase enzymes. Proteins, on the other hand, are broken down into their building blocks, amino acids, through proteolysis. Enzymes such as protease facilitate this process by breaking peptide bonds. These simpler molecules—sugars, fatty acids, and amino acids—serve as substrates for microbial activity, fueling subsequent biochemical reactions and energy production during anaerobic digestion [13].

2.1.2 Acidogenesis

The process by which fermentative bacteria transform intermediate products into lower fatty acids, including butyric, propionic, and acetic acids, as well as carbon dioxide and hydrogen, is known as acidogenesis. In trace amounts, lactic acid and alcohol are also produced. The soluble monomers are changed into volatile fatty acids, ethanol, hydrogen (H_2), and carbon dioxide (CO_2) by acid-forming bacteria, also known as acidogens [14].

2.1.3 Acetogensis

Acetogenesis is a critical step because it prepares substrates for methanogens, which use acetic acid and hydrogen to produce methane in the subsequent stage. The process also reduces the concentration of volatile compounds that could inhibit microbial activity. By generating acetates and hydrogen, acetogenesis ensures the efficient flow of energy and materials through the anaerobic digestion system.

2.1.4 Methanogenesis

At the end of digestion, biogas, primarily constituted of methane and carbon dioxide, is produced with the digested substrate. In the penultimate stage, strictly anaerobic methanogenic bacteria convert acetic acid (acetate) into methane (CH_4) and carbon dioxide (CO_2) [15].

Animal husbandry wastes, such as manure and other organic residues, are among the primary raw materials utilized for biogas production. These wastes are highly suitable for anaerobic digestion (AD), a biochemical process in which microorganisms break down organic matter in the absence of oxygen to produce biogas. The waste from animal husbandry is particularly advantageous for this process. Biogas, which basically consists of methane (CH_4) and carbon dioxide (CO_2), is a renewable energy source that can be utilized for electricity generation, heating, or as vehicle fuel. Additionally, the anaerobic digestion of these wastes contributes to waste management by reducing environmental pollution, controlling odors, and minimizing greenhouse gas emissions. The process also creates biofertilizers, which can be used to improve soil fertility and assist sustainable agriculture practices [16].

This study investigates the semi-continuous mesophilic anaerobic co-digestion of manure and vegetable waste at 35°C using lab-scale reactors. Methane yields of 0.3 m^3/kg VS were achieved at organic loading rates (OLRs) ranging from 0.3 to 1.3 kg VS/m^3/day, with methane content between 54% and 56%. However, increasing OLRs led to a decline in biogas production and methane yield, suggesting organic overload or insufficient buffering. The results emphasize the importance of optimizing operating conditions to enhance methane production while maintaining process stability [17].

Biogas technology provides an effective solution for managing slaughterhouse waste and livestock manure, while simultaneously producing renewable energy and supporting the Sustainable Development Goals (SDGs). By utilizing anaerobic digestion, this technology converts organic waste into biogas, a renewable energy source composed mainly of methane and carbon dioxide. This process mitigates environmental risks linked to untreated waste, such as water pollution and greenhouse gas emissions, while also reducing odors and the spread of pathogens. Additionally, biogas can be used for heating, cooking, and electricity generation, offering a sustainable alternative to fossil fuels and helping to lower carbon footprints. This approach addresses environmental, economic, and social challenges, making it a holistic and sustainable solution [18].

Although concerns about animal waste management in Punjab have grown, no comprehensive studies have been conducted to evaluate the biogas production potential of livestock manure. The expansion of animal farming has led to a rise in waste generation, making its disposal a significant challenge, particularly in rapidly urbanizing areas. This study aims to explore the feasibility of biogas production from animal waste in Punjab, providing policymakers with valuable insights into biogas technology as a sustainable energy solution. Additionally, this research aligns with efforts to achieve the Sustainable Development Goals (SDGs). Anaerobic digestion of agricultural and municipal waste offers a sustainable path for waste management and renewable energy production, generating both biogas and valuable fertilizers. A review of biowaste-to-bioenergy strategies highlights AD's alignment with the UN SDGs but also underscores the need for supportive policies and technological advances [19].

The resulting products from anaerobic digestion can serve as substitutes for natural gas and fossil fuels. During the AD process, the animal waste is converted into biogas as carbon dioxide (CO_2) and methane (CH_4) gases through a series of metabolic reactions. Anaerobic microorganisms break down organic components, with only a tiny portion of the biodegradable matter required for microbial development and the production of new cell mass, while the remainder is converted into biogas [20].

The decomposition of organic matter during anaerobic digestion is a intricate process that occurs in four distinct microbiological stages, each facilitated by specific microorganisms. In the initial stage, hydrolysis, complex organic molecules such as carbohydrates, proteins, and fats are broken down into simpler, soluble compounds like sugars, amino acids, and fatty acids by hydrolytic bacteria. This step is critical as it converts complex polymers into forms that can be metabolized by microorganisms.

The second stage, acidogenesis, involves fermentative bacteria transforming these simpler compounds into volatile fatty acids, alcohols, hydrogen, and carbon dioxide. Next, in acetogenesis, acetogenic bacteria further process these intermediates into acetic acid, hydrogen, and additional carbon dioxide, creating the necessary substrates for the final phase. The last stage, methanogenesis, is driven by methanogenic archaea, which convert acetic acid and hydrogen into methane and carbon dioxide the primary constituents of biogas. These interconnected microbial phases ensure the efficient breakdown of organic matter and the recovery of energy. [21].

The anaerobic digestion (AD) process is classified into four interconnected stages and each involving specific microbial activities and microorganisms. The first stage (hydrolysis) involves hydrolytic bacteria breaking down complex organic polymers like carbohydrates, proteins, and fats into simpler, soluble compounds like as sugars, amino acid, and fatty acids. Second in the acidogenesis and fermentative bacteria convert into volatile fatty acids, alcohols, hydrogen, and carbon dioxide (CO_2).

In the syntrophic acetogenesis step, syntrophic bacteria metabolize volatile fatty acids and alcohols into acetic acid, hydrogen, and carbon dioxide (CO_2) and creating substrates crucial for the final stage. At the end methanogenesis, methanogenic archaea employ acetic acid and hydrogen to create methane and carbon dioxide (CO_2), the principal components of biogas. Figure 2.2 provides a visual representation of these microbial stages, detailing the specific microorganisms involved and their roles in each phase, emphasizing the stepwise conversion of organic matter into biogas [22].

The economic viability of various biogas plant design used in Pakistani households. It compares the costs, efficiently, and sustainability of these systems, considering their potential to address energy shortages and environmental challenges in rural areas. The study evaluates the popular designs like as a fixed dome plant, floating drum plant, and plug flow type, analyzing their construction costs, operational efficiency, gas output, and maintenance needs. It highlights that fixed dome plants are the most cost beneficial in the larger time due to their low maintenance

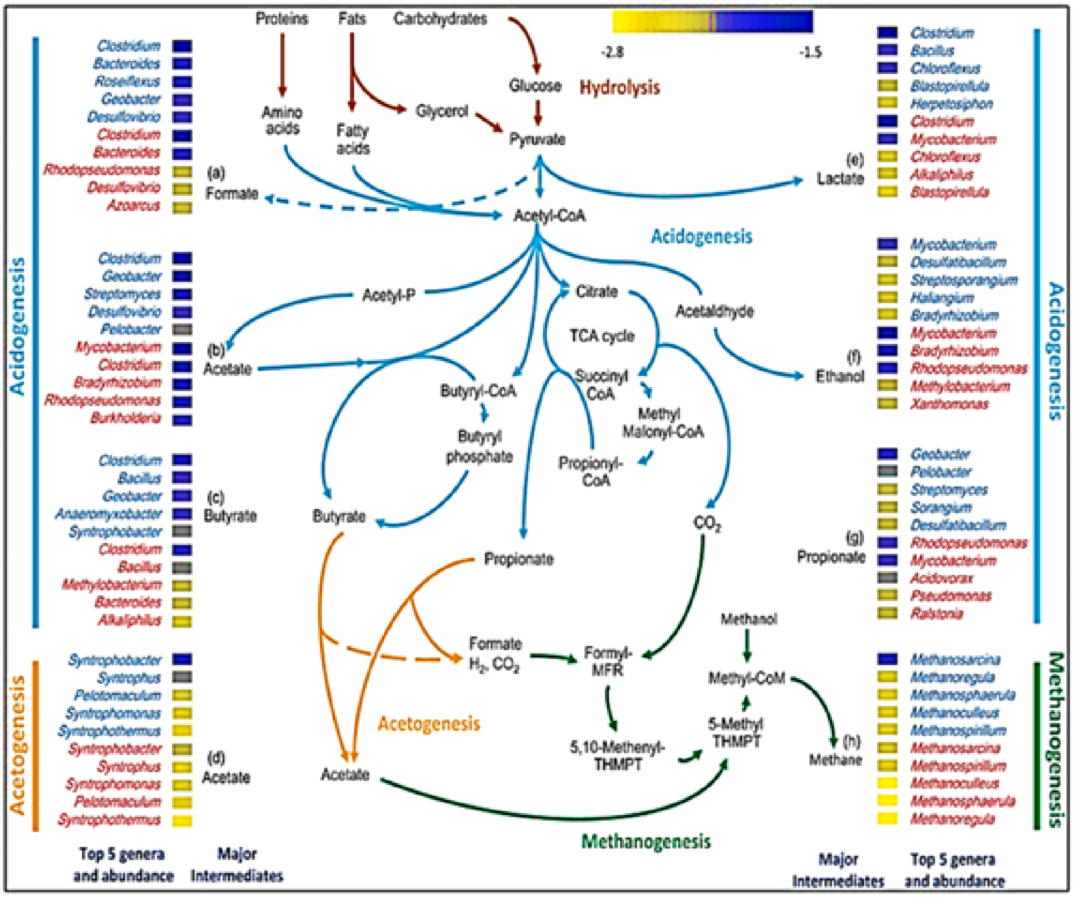


Figure 2.2: Stages of anaerobic digestion process

requirements and longer lifespan, though high initial installation costs remain a challenge for many households [24].

Biogas is a renewable energy source critical for reducing greenhouse gas emissions and advancing sustainable energy goals due to its dual role in waste management and energy generation. However, forecasting biogas production remains difficult because of variability in feedstock and co-digestion processes. A recent study tackled this issue by comparing traditional neural network models with uncertainty-aware methods. While simple neural networks yielded accurate point predictions, they failed to capture production uncertainty. To overcome this, the study adopted a hybrid approach combining the Box-Cox transformation for data normalization and the Lower Upper Bound Estimation (LUBE) method for generating reliable prediction intervals. This approach produced narrower and more precise prediction intervals, enhancing metrics like Prediction Interval Normalized Average Width (PINAW). Such improvements offer significant benefits for decision-making, enabling policymakers and investors to plan effectively and support Sustainable Development Goal 7 (SDG-7) by strengthening confidence in biogas as a viable renewable energy resource [25].

According to the study the potential for biogas energy production in Ardahan, a rural region in Turkey. With its extensive agricultural and pastoral activities, particularly a big cattle population, the area has adequate organic waste appropriate for biogas generation through anaerobic digestion.

This process can help meet local energy demands while also addressing waste management and environmental concern. The study assesses key factors such as the region's climate, availability of organic materials, and the economic viability of biogas projects. It suggests that biogas could serve as an alternative to fossil fuels, enhancing energy security and contributing to Turkey's renewable energy goals.

The paper also discusses the social and economic advantages of biogas development in Ardahan, such as job creation, better living standards, and rural development. The authors conclude that Ardahanpresents a strong opportunity for biogas energy, which could play a key role in local sustainable development. However, realizing this potential will require investment and supportive policies to promote biogas energy source [26].

Biogas production via anaerobic digestion (AD) of industrial organic waste and wastewater is a sustainable energy recovery method, though its efficiency depends heavily on operational conditions. To address this complexity, machine learning (ML) techniques have gained traction for predicting biogas yield. One study applied Support Vector Regression (SVR) with a Radial Basis Function (RBF) kernel to model biogas production in a full-scale digester treating fruit processing wastewater. The model used key operational parameters as inputs and achieved a strong regression coefficient ($R^2 = 0.8983 \pm 0.03$) and low mean square error ($MSE = 0.0047 \pm 0.0017$). Ten-fold cross-validation and hyperparameter tuning ensured robustness and accuracy. The results confirmed that SVR-RBF models effectively capture the nonlinear dynamics of biogas processes, enabling more accurate forecasting. This approach can support real-time monitoring and process optimization in industrial AD systems, highlighting the broader potential of ML-based modeling in enhancing biogas efficiency [27].

2.2 Electricity Generation

The Government of Pakistan is challenging a serious energy shortage with demand increasing by 11–13% annually. Back in 2006, the country needed 57.9 million tons of oil equivalent to meet its energy demands, and by 2020, this was expected to rise to 179 million TOEs. The problem escalated in 2012, when electricity shortages reached 8,500 MW during the summer due to heavy inductive loads. This led to daily power outages lasting 14 to 20 hours across the country, causing industries to under produce and exports to suffer. Over the years, Pakistan's electricity generation has dropped to nearly half, further deepening the crisis. As industries grow and the population increases, our need for energy keeps rising. Actually the fossil fuels are the main source of energy, but they also create serious environmental issue like air pollution and global warming [28].

The environmental consequences of using fossil fuels such as air pollution, GHG emissions and climate change have encouraged the development of other energy sources. Fossil fuels such as oil, natural gas and coal are a finite resource which means they will eventually be depleted. Studies predict that oil reserves could be exhausted by 2047, natural gas by 2068, and coal by 2140. These estimates underline the urgency of transitioning to more sustainable energy sources such as solar power, wind energy and hydroelectric power which do not rely on depleting natural resources [29].

The depletion of fossil fuel resources such as coal, oil and natural gas significant challenges for both energy security and the environment. These non-renewable resources are being extracted and consumed at unsustainable rates, leading to concerns about future shortages and rising energy costs. Moreover, the air pollution is increasing due to burning of fossil fuels as well as change the climate.. As a result, there is an increasing need to explore alternative energy sources that are more sustainable and environmentally friendly. Biogas energy is the best alternative of fossil fuels. Unlike fossil fuels, biogas is renewable and significantly reduces the environmental impact associated with waste disposal [30].

The potential of converting poultry waste into biogas for electricity generation. With Pakistan experiencing significant energy shortages, the study focuses on the large poultry industry as a source of biogas through anaerobic digestion, offering the renewable energy solution. The research highlights the process of producing biogas from poultry waste and evaluates its feasibility in term of both economic and environmental impact. Its finds that biogas source will play a vital in reducing the fossil fuels. However, barrier such as high initial setup costs, limited technical knowledge, and insufficient government backing need to be overcome. The paper advocate for increased infrastructure investment, financial support and policy intervention to enable wider adoption of biogas-based electricity generation, which cloud alleviate Pakistan's energy crisis and support environmental sustainability [31].

This feasibility of using biomass waste to produce biogas as a renewable energy source. Given Pakistan's ongoing energy crisis, the study highlights biogas as a sustainable solution for power generation, utilizing abundant waste materials like as livestock manure and municipal waste. By converting biomass into biogas, the country can generate clean energy, reduce greenhouse gas emission, and manage waste more efficiently. The research finds that biogas production from biomass is both economically viable and environmentally beneficial, reducing reliance on fossil fuels. The article also discusses technical and economic issues, such as the need for infrastructure investment and regulatory support to increase biogas usage. Despite these hurdles, the study concludes that biogas from biomass waste to enhance energy security and participate to renewable power generation in Pakistan, promoting environmental and economic benefits [32].

To investigate potential of a hybrid energy system combining solar and bio mass to fulfill the requirement of energy of Hatter Industrial Estate. The study focuses on the technical and economic feasibility of integrating these renewable sources into the on-grid system to reduce reliance on traditional energy sources. By modeling various sceneries, the authors access how well the system environmental impact. The hybrid system leverages Pakistan's abundant solar energy and bio mass resources to ensure reliable, continuous power supplies, even during low sunlight periods [33].

The feasibility of using animal waste for biogas and electricity generation. Turkey large livestock industry generates significant organic waste, offering an opportunity for renewable energy production through anaerobic digestion. The authors analyze the amount of animal waste, available focusing on livestock such as cattle, sheep, and poultry. They estimate the potential energy output from this waste and emphasize its environmental benefits, as biogas systems not only produce energy but also help manage animal waste more effectively. The paper also explores the potential for electricity generation by using biogas in cogeneration system, which can help meet local energy demands, particularly in rural areas [34].

According to the investigation the biogas potential in Turkey‘s Aegean region, focusing on the animal waste produce by its livestock sector. The region generates significant amount of organic waste from cattle, sheep and poultry which can be transferred into biogas through anaerobic digestion (AD). This renewable energy source offers a way to minimize the use on fossils fuels and meet local energy needs. The study evaluates the availability of animal wastes in the region and calculates the potential biogas output based on the amount and type of livestock waste produced. Moreover, this paper examines the possibility of using biogas for electricity generation through cogeneration systems, providing a stable and renewable energy source, especially in rural areas. With proper investment and supportive policies, biogas could significantly contribute to the region's sustainable energy goals, while also addressing environmental concerns and promoting economic growth [35].

The most energy effective way to use biogas which is produced from organic waste via anaerobic digestion the study explore three main application heat generation electricity production and transport fuel assessing which offers the greatest energy efficiency and overall benefits the authors evaluate each option based on conversion efficiency infrastructure needs and environmental impacts heat generation is the simplest and most energy efficient method particularly for localized industrial or residential heating electricity production often using combined heat and power (CHP) system allows biogas to serve both heating and electricity needs though it involves higher energy losses during conversion using biogas as transport fuel require more processing but offers a cleaner alternative to fossil fuels for vehicles heat generation is most efficient for local use while electricity and transport fuel offer border benefits depending on demand and available infrastructure [36].

Internal combustion engines (ICE) have been one of the most widely used technologies for converting biogas to electricity due to their reliability and efficiency. In biogas power plants, biogas is used as a fuel in ICE to drive the engine's rotation, which in turn drives an alternator to generate electricity. The efficiency of this conversion process typically ranges between 30% to 40%, depending on engine design, biogas composition, and operating conditions [37].

The use of ICE is particularly common in smaller-scale applications and decentralized biogas systems. The primary advantages of ICE are their ability to operate with a biogas compositions and the methane content is sufficient. However, challenges such as engine wear maintenance requirements and emissions of (NOx). To optimize efficiency and reduce emissions, innovations such as catalytic converters and engine modifications are being researched [38].

Biogas-fueled gas turbines (GTs) offer a high-efficiency option for biogas electricity generation, especially in medium to large-scale biogas plants. Gas turbines operate by igniting biogas in a combustion chamber, producing hot gases that spin a turbine connected to a generator. This technology can achieve efficiency levels of up to 40% to 60%, significantly higher than internal combustion engines, especially when used in combined cycle setups, where waste heat is used to produce additional power via a steam turbine [39].

Main benefits of gas turbines are their ability to handle larger volumes of biogas, making them suitable for centralized biogas plants. However, GTs requires a high level of biogas purity and stable composition for optimal performance, as contaminants such as sulfur and moisture can lead to turbine corrosion. Despite these challenges, ongoing developments in biogas upgrading and purification techniques are enhancing the feasibility of gas turbines for biogas-to-electricity applications. Micro turbines are a promising technology for biogas-to-electricity conversion, particularly in small-scale, distributed energy systems. These compact turbines are designed to operate at lower capacities (typically between 30 kW and 500 kW) and offer several advantages, such as lower emissions, reduced maintenance needs, and high efficiency in converting biogas to electricity [40].

Micro turbines are highly flexible in terms of fuel use, and they can efficiently run on low-quality biogas, making them an ideal choice for small-scale biogas plants in rural areas. The efficiency of micro-turbines can reach up to 35% to 40%, and when integrated with a CHP system, overall system efficiency can be significantly improved. Despite these benefits, micro-turbines face challenges related to their high initial capital cost and the need for biogas purification systems to prevent damage to turbine components. The ongoing development of more cost-effective micro-turbines and better biogas treatment methods may help to overcome these barriers in the future. Fuel cells represent one of the most efficient & clean technologies for converting biogas to electricity, with efficiencies often exceeding 50% in electricity generation and up to 85% in CHP configurations [41].

In this process, biogas is fed into a fuel cell where it reacts electrochemically, producing electricity, water, and heat. Unlike combustion-based technologies, fuel cells generate electricity without combustion, resulting in significantly lower emissions of pollutants such as NOx and particulate matter. They are particularly useful in decentralized and off-grid applications where environmental concerns are a priority. Furthermore, issues related to the durability of fuel cells when exposed to impurities in biogas, such as sulfur, need to be addressed to improve the long-term viability of this technology for biogas electricity generation. CHP systems are an increasingly popular selection for biogas electricity generation because they maximize the overall energy output by utilizing both the electricity and heat generated during the conversion process. These systems integrate electricity generation technologies (such as internal combustion engines, gas turbines, or micro-turbines) with heat recovery systems, which can be used for heating water, space heating, or industrial processes. The integration of CHP systems with biogas plants increases the overall efficiency of the process, with total energy recovery rates reaching up to 90% [42].

The dual output of CHP systems makes them especially valuable in applications where both electricity and heat are in demand, such as in agricultural or industrial biogas plants. However, the complexity and cost of installing and maintaining CHP systems can be a challenge for smaller-scale projects. Additionally, ensuring that both the heat and electricity needs are balanced to prevent waste of resources is crucial for the economic feasibility of these systems.

The economic viability of biogas-based electricity generation heavily relies on a thorough cost-benefit analysis, which evaluates both capital and operational expenditures against the revenue generated. Capital costs typically include the construction of the biogas plant, including the digesters, power generation equipment, and infrastructure for biogas collection and storage. Operational costs involve maintenance, labor, feedstock supply, and energy conversion [43].

A study emphasized that in rural or agricultural settings, biogas electricity generation often provides an attractive return on investment, particularly in areas with high availability of organic waste. However, the initial investment remains a barrier, and financing mechanisms, such as government subsidies, grants, and loans, play a critical role in making biogas electricity economically viable. The overall profitability is also determined by the price of power, which varies according to local legislation and market conditions. Government regulations and financial incentives have a considerable impact on the economic feasibility of biogas energy projects. Incentives like feed-in tariffs (FIT), tax credits, and subsidies can help lower the initial capital expenditure required to establish biogas plants [44].

A study highlighted that countries with strong policy support for renewable energy saw an increase in biogas electricity generation, with financial incentives improving return on investment (ROI). These policies not only make biogas projects financially feasible but also encourage private investment in biogas infrastructure. Moreover, the introduction of carbon pricing and renewable energy mandates often helps to create a favorable market for biogas-generated electricity, making it more attractive compared to fossil fuel-based energy. However, the effectiveness of such policies depends on the consistency and duration of government support [45].

A study showed that the impact of subsidies on biogas economics could vary based on the local regulatory environment and energy market conditions, making it crucial for policymakers to offer long-term stable incentives. Securing financing for biogas electricity generation projects is one of the primary challenges to their economic viability. Biogas projects often require large upfront investments for infrastructure, such as anaerobic digesters, power generation systems, and grid connection [46].

A study by discussed various financing options including public-private partnerships (PPP), venture capital and international climate finance which can help alleviate the financial burden on project developers. However, lenders and investors may be reluctant to fund biogas projects due to the high risks associated with feedstock availability, biogas yield fluctuations, and market instability. Additionally, biogas projects often face difficulty in securing long-term power purchase agreements (PPAs), which are essential for ensuring stable revenue streams. To mitigate these risks, some countries are adopting risk-reducing measures such as guaranteed prices for electricity and long-term purchase contracts. Despite these efforts, biogas electricity generation remains a high-risk investment in many regions. Small-scale biogas plants provide a cost-effective solution for rural or off-grid communities. These plants, typically producing under 1 MW of electricity, can significantly reduce energy costs for local farmers or small industries by utilizing waste material that would otherwise be discarded [47].

According to a study, small-scale biogas plants are particularly viable in areas with a steady supply of organic waste, such as agricultural residue or livestock manure. The study suggests that with reduced capital costs due to smaller-scale operations and shorter payback periods, small-scale biogas electricity systems have a lower financial risk compared to large-scale plants. However, they are still reliant on local conditions such as waste availability, local electricity tariffs, and financing options. Long-term financial sustainability is a critical consideration for biogas power plants. The economic success of biogas electricity generation is influenced by factors such as the durability of equipment, fluctuations in biogas production, and the price of electricity [48].

The long-term financial performance of biogas power plants and found that while the initial capital costs are high, the operational and maintenance costs are relatively low. The study suggests that, over time, biogas plants can become highly profitable, particularly when energy prices are high, or when there are opportunities for selling bio-fertilizer.

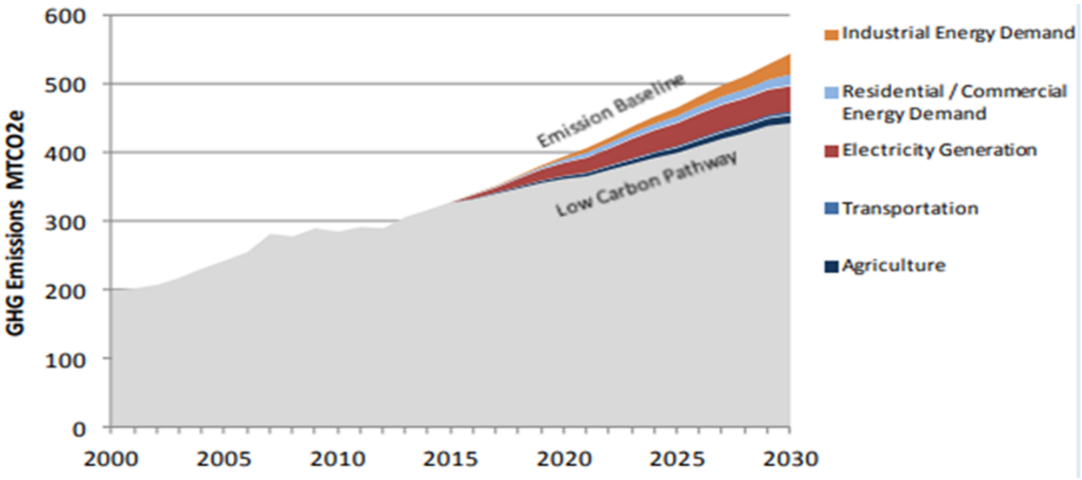
Additionally, the stability of biogas production is critical for ensuring a consistent power supply and minimizing operational downtime. The long-term profitability of biogas power plants is also highly dependent on the economic value of carbon credits and other environmental benefits. As carbon markets evolve, biogas plants may increasingly rely on revenue from carbon trading to improve their economic outlook [49].

2.3 GHG Emission

Pakistan ranks among the top ten countries most vulnerable to the impacts of climate change. As a signatory to the Paris Agreement, Pakistan has committed to addressing global climate change through its Nationally Determined Contributions (NDCs). These contributions emphasize climate change mitigation as a top priority, particularly through the adoption of energy-efficient appliances and process improvements to reduce CO_2 emissions.

According to the National GHG Inventory for 2014-15, Pakistan's energy sector accounted for approximately 331 million tonnes (MT) of CO_2-equivalent emissions, representing over 50% of the country's total GHG emissions. By achieving the target of saving 3 million tonnes of oil equivalent (MTOE) in energy over the next three years, Pakistan could reduce emissions by 6.4 MT of CO_2-equivalent, assuming an accelerated energy efficiency rate of 3.5%. The graph below illustrates the projected reduction in GHG emissions by 2030, with the National Energy

Efficiency and Conservation Authority (NEECA) expected to contribute around 6.5% of the total emission reduction 2023 [50].



18% percent below projected business as usual emissions by 2030, for a total reduction of about 97 Mt CO2eq.
5% is unconditional and 13% conditional on international support.
Source: Pakistan INDC Report

Figure 2.3: Illustrates the projected reduction in GHG emissions by 2030

Globally, the shift toward renewable energy sources is gaining momentum due to critical factors like climate change. With declining fossil fuel reserves and the ongoing search for new energy options, biogas production from organic waste has emerged as a promising alternative [51]. Converting organic waste into biogas presents an efficient solution for both waste management and energy generation. This type of waste, including food scraps, agricultural residues, sewage, and certain industrial by-products, constitutes a large share of landfill waste. If left untreated, it decomposes anaerobically, releasing methane which increase GHG emission and climate change. Through anaerobic digestion, however, methane is captured and transformed into a renewable energy source, effectively reducing emissions while promoting sustainable waste disposal [52].

Storing manure from animal barns helps reduce environmental impacts. Through specific processes, the stored manure generates biogas, benefiting both the environment and the economy. Today, alternative energy sources have gained significant importance as a means to reduce reliance on external energy supplies [53].

It investigates the possibility of biogas technology as a renewable energy alternative to meet the country's energy constraints, particularly in rural areas with limited access to power and conventional fuels. The study analyzers the financial aspects, including the initial investment, operational costs, and saving from replacing conventional fuels like firewood and kerosene. While the initial Investment, operational costs, and saving from replacing conventional fuels like firewood and kerosene. While the initial cost of setting up a biogas plant may be high, the long-term savings in energy expenses and the productions of organic fertilizer from biogas by products make it a cost-effective solution for households and communities.

The research also evaluates the performance and reliability of biogas plants, the environmental benefits, such as reducing GHG emissions and improving waste management. Despite these advantages, obstacles like limited technical expertise. Insufficient government support and financial constraints remain. The paper concludes that biogas plants provide significant financial and environmental benefits and suggests policy measures and Incentives to encourage broader adoption in Bangladesh [54].

Through this study explores the growth and development of biogas plants in Italy, focusing on the role of subsidies, costs, biogas composition, and engine emissions. The study highlights the increasing trend in biogas plant installations, largely driven by government incentives that have made renewable energy investments more attractive. Financial aspects are a key focus, with the paper emphasizing the crucial role of subsidies in ensuring the economic feasibility of biogas plants. It outlines the costs related to constructing and maintaining these plants, showing that without government support, the financial viability of many projects would be significantly reduced. The research also delves into the composition of biogas produce in Italian plants, predominantly consisting of methane and carbon dioxide, and its effectiveness in generating electricity. Furthermore, the paper examines the emissions produced by biogas engines, which show a notable reduction in harmful pollutants compare to traditional fossil fuels [55].

The researcher investigates methane emissions from biogas plants using laser absorption spectrometry. Methane, a significant greenhouse gas, can escape during biogas production, potentially diminishing the environmental benefits of this renewable energy source. The study aims to accurately measure these emissions to evaluate the efficiency and sustainability of biogas plants. By employing laser absorption spectrometry, the research enables precise, real-time monitoring of methane leaks at various stages of the biogas production process. This advanced technique provides detailed data on methane emissions, crucial for improving plant performance and minimizing environmental impact. While biogas is considered a cleaner energy alternative, the study underscores that unaddressed methane leaks can significantly reduce its overall environmental benefits. The results demonstrate that laser-based systems are highly effective in detecting even minor methane leaks, offering actionable insights to optimize plant operations and reduce emissions [56].

Biogas technology is used for animal wastes that would otherwise harm the environment is put to good use. Instead of polluting soil and water, these waste materials are processed in biogas facilities to produce energy. The process not only generates renewable power but also creates a nutrient-rich organic fertilizer that can be returned to farmlands, supporting sustainable agriculture [57].

Through this study the economic viability and long-term benefits of setting up a biogas plant as an alternative energy source. It highlights the potential of biogas technology to provide a sustainable, cost-effective solution for energy demands while addressing waste management challenges. By analyzing parameters such as initial investment, operational costs, payback period, and revenue generation from biogas and by-products like bio-fertilizer, The study demonstrates the viability of incorporating biogas systems into small-town energy infrastructures [58].

The study evaluates whether bio gas technology can meet the town’s energy demands while offering economic and environmental benefits. Key aspects covered include the availability of raw material like organic waste, plant design, construction and operational costs, potential energy output. The paper assesses the cost-effectiveness by comparing the initial investment with long-term energy savings and environmental gains, such as reduced fossil fuels use and improved waste management [59].

The researcher investigates the potential for bio gas production using animal manure and agriculture residues across turkey. The study aims to identify regions with high bio gas generation capacity by analyzing organic waste from livestock and agriculture activities. The research supports Turkey's renewable energy goals by highlighting the underutilized bio gas resources that could help meet the country's energy demands while enhancing environmental sustainability. The paper maps the distribution of waste resources, including animal manure and crop residues, to estimate their bio gas production potential. It evaluates the possible energy output from these resources and examines the economic feasibility of establishing bio gas plants in different regions [60].

Animal manure is an abundant organic waste that holds significant potential for biogas production, particularly due to its nutrient-rich composition and availability. Among the different types of manure, cattle and chicken manure are especially noteworthy because of their consistent and large-scale accumulation. This is largely attributed to the high reproductive rates of these animals and their widespread use in agricultural and industrial farming systems. Cattle manure, rich in cellulose and hemicelluloses, provides an ideal substrate for anaerobic digestion, a process where microorganisms break down organic material in the absence of oxygen to produce biogas. Similarly, chicken manure, high in nitrogen and phosphorus, is highly biodegradable and contributes to efficient biogas generation. The utilization of such manure not only mitigates the environmental problems associated with its disposal, such as methane emissions and water contamination, but also supports renewable energy production. This dual benefit underscores the importance of leveraging animal manure for sustainable energy systems [61].

Anaerobic treatment is a highly effective method for addressing odor issues caused by animal manure while offering additional environmental and economic benefits. Additionally, improper disposal can lead to runoff, contaminating water sources with pathogens, nitrates, and other pollutants, posing serious health risks. Through anaerobic digestion (AD) microorganisms break down organic matter in an oxygen-free environment. This process not only eliminates unpleasant smells but also converts the manure into valuable by-products like biogas, which can be used as other energy source, and nutrient-rich bio-fertilizer. By implementing anaerobic treatment systems, farms can achieve sustainable waste management, improve local air and water quality, and support environmental health [62].

The feasibility of investing in biogas plants on dairy farms by analyzing energy demand and economic potential. It focuses on utilizing dairy farm waste, primarily cow manure, as renewable resource for biogas production the study assesses the energy that can be generated from this waste and evaluates the financial viability of setting up biogas plants in dairy farming operations. The analysis takes into account factors such as the farm‘s energy requirements, the costs of building and operating the biogas plant, and the potential benefits, including energy saving and income from selling surplus energy. The paper emphasis that biogas plants can help reduce dependence on traditionally energy sources while providing environmental benefits, such as improved waste management and lower greenhouse gas emissions [63].

The viability of using biogas produced from vinasse, a byproduct of sugarcane processing, as substitute for diesel in sugarcane transport fleets. The study aims to determine whether switching from diesel to vinasse biogas is both cost-effective and environmentally sustainable for sugarcane industry. Using a portfolio optimization approach, the analysis considers factors such as biogas production costs, fuel price volatility, operational expenses, and potential saving. The goal is to identity the optimal balance between diesels and biogas usage to reduce costs while maintaining fleet efficiency and minimizing environmental impact. The result indicates that replacing diesel with vinasse biogas can generate significant cost savings and lower greenhouse gas emissions, making it a promising alternative fuel for the industry. The study concludes that with the right investment and infrastructure, vinasse biogas can enhance the economic and environmental sustainability of sugarcane transport operations, contributing to a greener energy future for the sector [64].

The feasibility of producing biogas from animal waste in this region, which has significant livestock industry. The significant organic waste produced by cattle, sheep, and poultry can be transformed into biogas through anaerobic digestion (AD) offering a renewable and sustainable energy solution for the region. The authors assess the availability of animal waste and estimate the potential for biogas production based on the waste generated by different livestock types. They calculate the potential energy output and its capacity to meet local energy needs [65].

In this paper the researcher examines the feasibility of establishing biogas plants in turkey to convert animal manure into energy with turkey's large livestock sector a significant amount of organic waste especially mature is produced which can be used for biogas production through anaerobic digestion. This process can address energy demand while promoting sustainable waste management the study accesses the regional distribution of livestock farming and estimates the amount of mature available for biogas generation it evaluates the technical and economic factors involved in setting up biogas plants including plant size and energy requirement the environmental benefits are also highlight such as reducing GHG emissions and modify the waste management practices additionally this paper discusses the socio economic advantages including job creation and rural development biogas plants could serve as a decentralized energy source particularly benefiting rural area [66].

Animal waste is a significant form of organic waste that, if not properly managed, can pose serious environmental risks. It is rich in nutrients like nitrogen (N) and phosphorus (P), which can lead to nutrient imbalances and pollution. Moreover, animal manure may contain residues of antibiotics, growth hormones, and heavy metals, further impacting ecosystems. The presence of microorganisms in manure also raises concerns about environmental contamination and potential health risks for humans [67].

Improper disposal of animal manure poses significant risks to air, soil, and water quality by releasing pollutants, contributing to eutrophication, and emitting harmful gases such as methane and ammonia. Anaerobic digestion (AD) provides a sustainable solution to these challenges. Through the controlled decomposition of manure and slurry in oxygen-free environments, AD produces biogas, a renewable energy source with high methane content, which can replace fossil fuels and reduce greenhouse gas emissions. The byproduct of this process is a nutrient-rich digestate that serves as a high-quality organic fertilizer, providing essential nutrients like nitrogen and phosphorus in forms more readily absorbed by crops. AD also minimizes odor emissions and destroys harmful microbial pathogens and parasites present in raw manure, making the process safer for human health and improving environmental quality, especially in agricultural communities [68].

Biogas is a renewable energy source produced through anaerobic fermentation, a natural biological process in which microorganisms decompose organic materials in an oxygen-free environment. This technique is widely used to process various organic wastes, such as animal manure, agricultural residues, food waste, and sewage sludge. As these materials break down, they generate a mixture of gases, primarily methane (CH_4) and carbon dioxide (CO_2), along with trace amounts of other gases like hydrogen sulfide (H_2S). By converting waste into energy and valuable byproducts, biogas production not only helps reduce greenhouse gas emissions but also enhances waste management and supports a circular economy [69].

Biogas production from agricultural waste plays a significant role in reducing greenhouse gas (GHG) emissions by diverting organic waste from landfills and providing a renewable energy source. A study by researcher highlighted that by capturing methane a potent greenhouse gas—during the anaerobic digestion of agricultural residues such as crop leftovers, manure, and food waste, biogas systems effectively mitigate methane emissions that would otherwise occur from open-air decomposition. In regions where agriculture is the dominant economic activity, biogas plants can provide an alternative to traditional waste management methods. The study showed that biogas energy not only reduces methane emissions from waste but also offsets CO_2 emissions from fossil fuel-based energy generation. The study concludes that biogas production from agricultural residues is an effective strategy for both waste management and climate change mitigation. Biogas, as a renewable energy source, plays an important role in mitigating greenhouse gas emissions in the energy sector [70].

According to the review, biogas systems trap methane during anaerobic digestion processes, which would otherwise escape into the atmosphere as a powerful greenhouse gas. The use of biogas to generate electricity or heat reduces the need for fossil fuels such as coal and natural gas, resulting in a net reduction in GHG emissions. The study also found that, when compared to other renewable energy sources, biogas has the distinct advantage of producing both electricity and heat energy via Combined Heat and Power (CHP) systems. These CHP systems can attain efficiencies of over 80%, considerably lowering the carbon footprint of energy production. Biogas helps to mitigate climate change by replacing fossil fuels and utilizing waste products, as well as supporting the worldwide transition to a low-carbon economy. The lifecycle assessment (LCA) of biogas systems is crucial to evaluating their overall influence on GHG emissions [71],

A study by conducted an LCA on biogas plants, assessing the carbon footprint reduction potential from feedstock collection, biogas production, electricity generation, and digestate utilization. The study found that biogas systems are highly effective at reducing GHG emissions, especially when the feedstock includes waste materials like manure and food scraps, which would otherwise emit methane in landfills. The LCA showed that biogas energy systems can reduce overall GHG emissions by up to 80% compared to traditional fossil fuel-based power generation, considering both avoided emissions from fossil fuels and methane capture. However, the study also pointed out that the emissions from transportation, plant operation, and maintenance need to be considered in the overall carbon balance. Despite these emissions, the reduction in methane from waste management and the displacement of fossil fuels make biogas a highly beneficial technology for climate change mitigation. A key contribution of biogas in reducing greenhouse gas emissions is its role in mitigating methane emissions from organic waste [72].

A study by focused on the potential of biogas in mitigating methane emissions from landfills, agricultural practices, and wastewater treatment plants. The authors noted that methane is a significantly more potent greenhouse gas than CO_2, with a global warming potential (GWP) 25 times greater over a 100-year period. By capturing methane through anaerobic digestion, biogas systems provide a highly effective means of reducing methane emissions. The study also explored how integrating biogas technology into existing waste management and wastewater treatment processes could contribute to national climate targets. It concluded that biogas offers a scalable solution for reducing GHG emissions, especially when integrated into waste management systems and coupled with policies such as carbon pricing and renewable energy incentives. Biogas production plays a vital role in the circular economy by transforming waste into valuable resources, helping to reduce greenhouse gas emissions [73].

How biogas technology integrates with circular economy principles to reduce emissions while generating renewable energy. The study found that biogas systems not only prevent methane emissions from organic waste. The study demonstrated that biogas systems, when implemented at scale, can reduce net GHG emissions by decreasing reliance on fossil fuels and mitigating emissions from waste management practices. Furthermore, by recycling nutrients through digestate application in agriculture, biogas plants support soil health and reduce the need for synthetic fertilizers, which have their own carbon footprint. The authors concluded that biogas energy is a powerful tool for enhancing sustainability and contributing to the global reduction of GHG emissions [74].

According to study the potential of agricultural waste as a feedstock for biogas production, highlighting its role as a sustainable green energy solution. The paper focused on the process of anaerobic digestion, where agricultural residues such as crop leftovers, animal manure, and food waste are converted into biogas. These feedstocks are abundant and often underutilized, making them ideal for biogas production. The study emphasized that biogas systems could contribute significantly to reducing the carbon footprint of agricultural operations. By utilizing organic waste, biogas not only provides a renewable energy source but also helps in mitigating methane emissions that would otherwise occur from waste decomposition in open environments [75].

The role of biogas, as a renewable energy source for rural development, revealing its potential to provide reliable power in remote and off-grid areas where conventional energy infrastructure is inadequate or unavailable. In rural communities, biogas systems utilize locally sourced organic waste, such as animal manure, crop residues, and food scraps to generate clean electricity and heat as compare to fossil fuels. The research emphasized the dual benefits of biogas: not only does it serve as a sustainable energy source, but it also helps manage waste by converting it into bio-fertilizer.

Additionally, biogas production can boost local economies by creating jobs and reducing reliance on costly fossil fuels.. The paper argued that biogas technology, especially when integrated into agricultural and rural development policies, can empower local communities, reduce energy poverty, and support rural economic development in a sustainable manner [76].

In a comprehensive review, discussed biogas as a green energy solution for both waste management and climate change mitigation. The paper outlined how anaerobic digestion, the process by which biogas is produced, plays a crucial role in waste-to-energy conversion. Biogas facilities lessen the environmental impact of landfills by treating organic waste such as municipal solid waste, agricultural waste, and sewage, which would otherwise produce methane, a potent greenhouse gas. The study also highlighted the climate change mitigation potential of biogas. By replacing fossil fuels like coal, oil, and natural gas, biogas systems not only provide renewable energy but also contribute to the reduction of CO_2 and methane emissions.

The paper concluded that biogas systems can significantly reduce the carbon footprint of waste management processes and play a pivotal role in achieving global climate goals, especially in urban areas with high organic waste generation [77].

An in-depth analysis of the economic and environmental benefits of biogas as a green energy source. The paper emphasized that biogas is not only a sustainable energy source but also a cost-effective alternative to fossil fuels, especially in rural areas where energy access is limited. The study found that biogas production systems can be economically viable, with payback periods typically ranging from 3 to 7 years, depending on the scale and feedstock availability. Biogas systems provide significant environmental benefits by lowering greenhouse gas emissions, including methane and CO_2, which would otherwise be released through waste disposal methods like landfilling and open burning. Additionally, using biogas as an energy source helps minimize the environmental footprint of conventional energy production by replacing fossil fuels. The paper concluded that biogas technology offers a promising pathway for both economic development and environmental sustainability, particularly in developing countries [78].

The biogas fits into the circular economy model, where waste materials are continuously reused to generate energy and other valuable by-products. The authors argued that biogas is a crucial component of the circular economy, providing a sustainable energy solution while simultaneously addressing waste disposal challenges. The process of anaerobic digestion (AD) converts animal waste into biogas, which can be used for electricity generation, cooking, or transportation fuels. The digestate generated during the process provide as a nutrient-rich organic fertilizer, decreasing reliance on chemical fertilizers and enhancing soil health.

The study also emphasized that biogas production helps reduce the demand for landfill space and its environmental consequences, such as methane emissions into the atmosphere. By turning waste into energy, biogas contributes to resource efficiency, lowers environmental pollution, and supports the sustainable management of organic materials. The authors concluded that biogas is an essential green energy solution for advancing the circular economy and achieving long-term sustainability goals [79].

2.4 Bio-Fertilizer as by Product

The anaerobic fermentation process converts wastes and residues from various sources into valuable products, including biogas as a renewable energy source and fermented manure as a potential fertilizer the anaerobic digestion process produces fermented solid and liquid materials left after the digestion of organic matter. It contains essential nutrients such as NPK making it an excellent organic fertilizer for plants and agricultural etc. The use of fermented manure enhances soil health, improves crop yields, and reduces the need for synthetic fertilizers, contributing to more sustainable farming practices [80].

Anaerobic fermentation can take place in both natural settings and controlled environments, ranging from small to large-scale operations. The fermented fertilizer produced during biogas generation possesses qualities ideal for agricultural use, providing essential nutrients that plants can absorb easily for healthy growth The fermented fertilizer produced in biogas plants is rich in essential nutrients like (NPK) nitrogen, phosphorus, and potassium key components for plant growth. Unlike synthetic fertilizers, which can harm the environment through runoff and soil deterioration, nutrients in digestate are in forms that plants can easily absorb, supporting stronger crops. The high organic content of the fertilizer also improves soil structure, moisture retention, and microbial activity, further enhancing soil fertility and supporting sustainable agricultural practices. This makes the use of fermented manure from biogas production a valuable and environmentally friendly alternative to chemical fertilizers [81].

The benefits of utilizing digestate, a by-product of biogas production, as an organic fertilizer in agriculture. The study focuses on the economic and environmental advantages for Ukraine‘s agricultural sector, in line with the European Green Deal‘s goals of reducing carbon emissions and promoting sustainable farming. The research highlights that replacing chemical fertilizers with digestate improves soil health, enhance crop yields, and reduces farming costs. Digestate, rich in essential nutrients such as nitrogen, phosphorus, and potassium, enhances soil fertility while reducing reliance on expensive synthetic fertilizers that can harm the environment. Using digestate in agriculture not only improves economics efficiency but also supports the European Green Deal by reducing greenhouse gas emissions and promoting a circular economy [82].

The potential of biogas technology to provide a renewable energy solution for Debre Berhan University. Faced with growing energy demands and high fuels costs, the university seeks alternatives to reduce its dependence on traditional energy sources; like firewood and grid electricity. The project focuses on the design and implementation of biogas facilities that transform organic waste, such as food scraps and animal manure, into biogas via anaerobic digestion.. This biogas can be used for coking, heating, and electricity generation, offering an eco-friendly energy solution. The research finds that biogas technology not only lowers energy costs but also reduces environmental impact by cutting carbon emission and managing waste. The by-product, organic fertilizer, can support agricultural activities [83].

Economically, biogas plants provide households with a clean and affordable energy source, reducing their reliance on costly and polluting fuels. This transition also frees up time for women, who typically spend hours collecting firewood, allowing them engage income-generating activities. Health benefits are notable, as biogas significantly reduces indoor air pollution caused by burning biomass, improving air quality and reducing respiratory illnesses, particularly among women and children. In agriculture, the digestate produced as a by-product of biogas serves as a nutrient-rich organic fertilizer, enhancing soil fertility and increasing crop yields, contributing to food security and economic stability for rural families [84].

Using fermented fertilizer keeps the soil healthy, improves its structure, and boosts its natural nutrient content. Fermented fertilizers are rich in beneficial microbes and organic matter. These microorganisms help break down organic material in the soil, making nutrients more accessible to plants, which contributes to healthier soil. Fermented fertilizers can help improve the soil's texture by increasing its ability to retain moisture, air, and nutrients, making it more friable (easy to work with) and better for plant growth. Fermented fertilizers often contain a variety of nutrients like nitrogen, phosphorus, and potassium, along with trace minerals. These nutrients replenish the soil's natural fertility, supporting plant growth without relying on chemical fertilizers [85].

Fermented manure is a blend of partially broken-down organic materials, microbial biomass, and inorganic compounds. These are plant and animal wastes that have started decomposing but are not fully broken down yet, providing a slow-release source of nutrients. This is to the beneficial microorganisms present in the manure, which help further decompose organic matter and improve soil health. These are naturally occurring or added minerals like nitrogen, phosphorus, and potassium that enhance the nutrient content of the manure. Fermented manure is a nutrient-rich material containing a mix of organic matter, helpful microbes, and essential minerals to improve soil fertility and plant growth [86].

Fermented fertilizer, the main by-product of the biogas production process, holds significant value for plant cultivation and is expected to become a sustainable alternative to conventional mineral fertilizers. Fermented fertilizer is created during the generation of biogas. It is rich in nutrients and beneficial microorganisms, making it effective for promoting plant growth and soil health. Unlike synthetic fertilizers, fermented fertilizer is eco-friendly, reduces reliance on chemical inputs, and supports sustainable farming practices. Fermented fertilizer from biogas production is a nutrient-rich, environmentally friendly alternative to traditional fertilizers, contributing to sustainable agriculture [87].

Fermented manure preserves essential plant nutrients, including trace components required for plant growth, such as nitrogen, phosphate, and potassium. Zinc, iron, and manganese are minor yet essential elements for plant health and development. The fermentation process preserves these nutrients and components, making them available to plants when the manure is utilized as fertilizer. Fermented manure maintains both vital nutrients and critical trace elements, making it extremely advantageous to plant growth [88].

This process is highly efficient for converting animal manure into biogas due to its rich composition of organic matter and high methane-generating potential. Animal manure contains volatile solids that are decomposed by bacteria during digestion, producing biogas primarily composed of methane (CH_4) and carbon dioxide (CO_2).The methane concentration in biogas, typically ranging from 60–80%, makes it a valuable energy source for electricity generation, heating, and even as a vehicle fuel. Besides energy production, anaerobic digestion of manure significantly reduces odor emissions, destroys harmful pathogens, and minimizes greenhouse gas emissions, particularly methane that would otherwise escape into the atmosphere from untreated manure. The process also produces digestate, a nutrient-rich byproduct that can be used as an organic fertilizer, enhancing soil fertility and promoting sustainable agricultural practices [89].

Cattle manure is widely regarded as the primary material for biogas production globally, largely because of the substantial daily output of manure produced by cattle compared to other livestock. Each cow can generate significant amounts of manure daily, providing a steady and reliable feedstock for biogas plants. Additionally, cattle manure has an ideal balance of organic matter, including cellulose and hemicellulose, which makes it well-suited for anaerobic digestion. Its abundance in agricultural regions further enhances its accessibility and cost-effectiveness. This makes cattle manure a cornerstone resource for renewable energy initiatives, addressing energy demands while promoting sustainable waste management practices [90].

Biogas, derived from organic wastes such as animal manure, agricultural residues, food waste, and sewage sludge, offers immense potential to address energy demands in power generation and transportation. Through anaerobic digestion, these wastes are converted into biogas, a renewable energy source primarily composed of methane (CH_4) and carbon dioxide (CO_2). The high methane content makes biogas a reliable and efficient fuel for producing electricity and heat or as a substitute for natural gas in transportation. One of the significant advantages of biogas production is its dual benefit in waste management and renewable energy generation. By utilizing organic waste, biogas systems reduce landfill usage and greenhouse gas emissions while creating a sustainable energy source. Furthermore, the process produces bio-fertilizer (digestate), a nutrient-rich byproduct containing nitrogen, phosphorus, and other essential nutrients. This bio-fertilizer enhances soil fertility, reduces reliance on synthetic fertilizers, and supports sustainable agricultural practices, completing the cycle of resource efficiency and environmental protection [91].

Converting waste into energy using technologies such as biogas production from animal waste is a highly effective strategy for sustainable energy development, especially in developing countries. Biogas systems utilize anaerobic digestion to transform organic waste into renewable energy, reducing reliance on fossil fuels while addressing waste management challenges. The process generates methane-rich biogas for electricity, heating, and transportation, contributing to energy security. Additionally, the byproduct, a nutrient-rich bio-fertilizer, supports sustainable agriculture by minimize the chemical fertilizer. This approach not only mitigates greenhouse gas emissions but also promotes economic growth, environmental protection, and resource efficiency, aligning with global sustainability goals. [92].

Bio-fertilizers are natural substances containing living microorganisms that promote plant growth by increasing nutrient availability in the soil. They enhance soil fertility through nitrogen fixation, phosphate solubilization, and production of plant growth-promoting substances. Common examples include nitrogen-fixing bacteria like Rhizobium, phosphate-solubilizing bacteria, and mycorrhizal fungi [93].

Unlike chemical fertilizers, bio-fertilizers are eco-friendly, non-toxic and help to reduce the environmental footprint of agriculture. They play a crucial role in sustainable farming practices by improving soil structure, boosting crop yields, and reducing dependency on synthetic inputs. Recent advancements include nano-bio-fertilizers and genetically engineered microbial strains, which enhance nutrient efficiency. With increasing global focus on climate change and food security, bio-fertilizers offer a viable solution to address agricultural challenges, particularly in degraded and marginal soils. Widespread adoption requires overcoming challenges like limited awareness, production scalability, and regulatory hurdles. Their potential for restoring soil health and mitigating climate impacts makes them essential for modern agriculture [94].

2.4.1 Bio-Fertilizers and Global Food Security

Bio-fertilizers are essential in tackling global food security, providing a sustainable and environmentally friendly alternative to chemical fertilizers. As the global population continues to grow, the demand for food is expected to rise by 70% by 2050, according to FAO estimates. Traditional agriculture, heavily reliant on synthetic fertilizers, contributes to soil degradation, water pollution, and greenhouse gas emissions, making it unsustainable in the long term. Bio-fertilizers, containing beneficial microorganisms like Rhizobium, Azotobacter, and mycorrhizal fungi, enhance nutrient availability, improve soil health, and boost crop productivity. They are particularly effective in nutrient-deficient and degraded soils, enabling higher yields while minimizing environmental harm. Moreover, bio-fertilizers support the growth of staple crops like wheat, rice, and maize, essential for global food supplies. Their adoption is especially significant in developing regions, where access to synthetic inputs is limited. However, challenges such as farmer awareness, storage, and scalability need to be addressed to maximize their potential. By reducing dependency on chemical fertilizers, bio-fertilizers can contribute to sustainable agriculture and ensure a resilient global food system [95, 96].

2.5 Research Gap

- Although, there are few studies available related to biogas plants in Pakistan; however, a comprehensive economic feasibility of biogas plan is seldom discussed.
- There is a lack of research quantifying the actual methane emissions from biogas plant.
- There is a significant research gap where the collective impact of manure management, biogas production, electricity generation, bio-fertilizer application, and their associated GHG emissions and carbon footprint has not been comprehensively studied.
- The literature lacks any direct comparison between biogas and solar energy.
- Existing literature lacks future-oriented analysis, and no prior study has presented predictive modeling of biogas potential and GHG emissions in Pakistan up to 2030.
- There is no available tool or model in the literature that provides a user-friendly calculation of biogas potential, highlighting the novelty of the biogas capacity calculator developed in this study.

Chapter 3

Research Methodology and Quantitative Analysis

3.1 Introduction

The term ‘research methodology’ refers to the scientific approach used to gather and process necessary information. Keeping this definition in mind, the present study has been conducted.This section outlines the methods used to gather and analyze data for the feasibility study conducted in Punjab. Data was obtained from the Ministry of Bureau & Statistics Pakistan along with local livestock farmers raising cattle, sheep, goats, chickens, and horses. The collected information included respondents’ basic details like location, age, family size, and occupation, while the key focus was on livestock numbers to estimate available manure quantities for biogas production from cattle, cow, sheep, goats, chickens and camel/horses/donkey. The study also examined current energy sources to compare with potential biogas output and assess economic viability of biogas system and solar system.After data analysis, select five parameter of biogas plant as under:

1. Animals Waste Potential

2. Biogas Generation Capacity

3. Electric Potential

4. Greenhouse Gas Emission

5. Bio-Fertilizer

As illustrated in Figure 3.1, the flowchart summarizes the methodology approach.

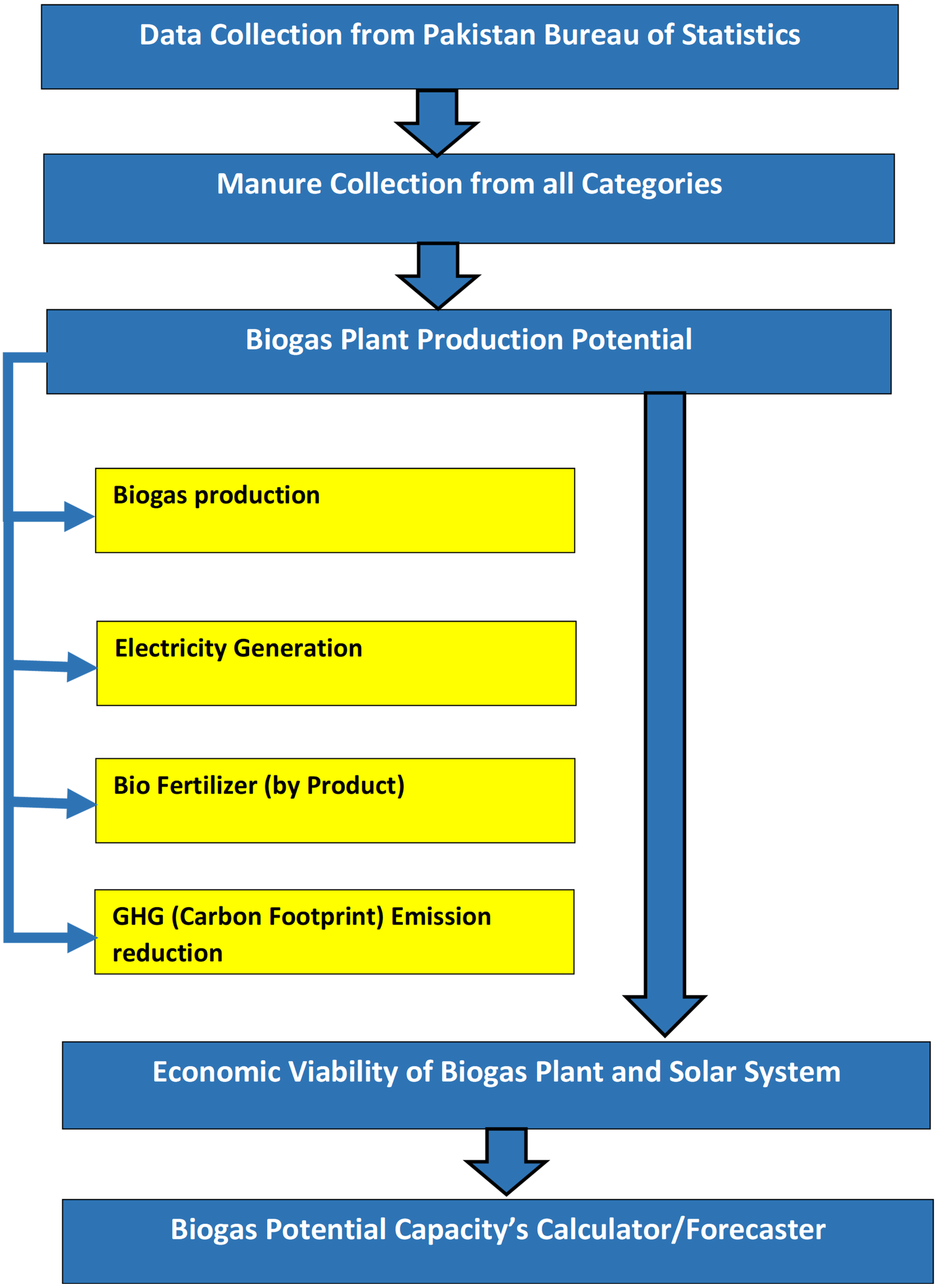


FIGURE 3.1: Flow Chart of Research Methodology

3.2 Tools & Approaches for Feasibility Study of Biogas Plants

To conduct the feasibility study of biogas plants, information about substrate/feedstock availability is necessary. Biogas yield provides the ultimate biogas production per amount of substrate added under defined conditions. The methane content present in the biogas helps to calculate the energy production. Biogas yield in advance is determined after knowing the nature of substrate utilized.

A reasonable average quantity of substrate produced daily is assumed according to the species of cattle and other animals. When the information about the substrate is known, the value of biogas and methane yield from the nature of substrate can be taken from previously conducted experiments, models and literature. Energy potential from the produced biogas is calculated and compared with solar system.

For economic analysis, a basic dimensioning of the biogas plant is done where the size of digester volume is calculated as per the quantity of substrate added per day. A simple economic analysis is carried out where biogas will be used as energy source for cooking purposes replacing butane cylinder in the case study region.

It means that the current price of energy from solar PV is equivalent to the energy provided by the biogas produced. The possibility of plant to be feasible if a subsidy of certain investment is provided is also calculated. For feasibility of large-scale biogas plants, nearby farms are clustered in one location and a combined result for biogas yield, energy yield and other economic parameters are calculated.

All the technical and economical evaluations for each category are done in Microsoft Excel. Various mathematical functions and logical statements are used to ease the calculations. For calculation of manure collection, biogas production, electricity generation, bio-fertilizer and GHG emission.

3.3 Conceptual Framework of Biogas Plant

Figure 3.2 illustrates the conceptual framework of the study, which is broadly divided into two systems: 'internal' and 'external.' The internal system refers to the processes and functioning of the biogas plant, while the external system encompasses factors that influence the internal system, such as the construction of the biogas plant and the production of biogas. In simpler terms, the internal system provides an overview of how the biogas plant operates. The arrows from input to output represent the sequence or flow of the system. The system boundary separates the internal and external systems in the use cases.

The 'internal system' (biogas production and process) is complex, but in this framework, a simplified model is presented for easier understanding, as this study partially focuses on biogas plant technology. The biogas production process begins with the input of various substrates, such as animal manure, municipal solid waste, industrial wastewater, and crop residues. However, for this particular plant, the input is animal manure. All impurities are removed from the animal manure before digestion to ensure optimal biogas production. The arrow crossing the internal system boundary indicates that the input substrates are produced externally and transported into the internal system for biogas production. In the second phase, the substrate is mixed to enable fermentation.

The third phase involves anaerobic digestion, which is the core process of biogas production. Anaerobic digestion occurs in three stages: hydrolysis, acidification, and methanogenesis. The fourth and final phase is the output, which takes the form of biogas. The produced biogas can be utilized for energy production, cooking, combined heat and power, and, if upgraded, can even be used as vehicle fuel. The organic-rich digestate can be used as a natural fertilizer for farming.

The 'external system' is connected to the internal system, with double-ended arrows representing the simultaneous interactions between both systems. The 'external system' is designed to demonstrate how various stakeholders and institutions, such as the government, environment, community, health sector, agriculture, energy, and economy, are affected by the biogas plant. More details on this will

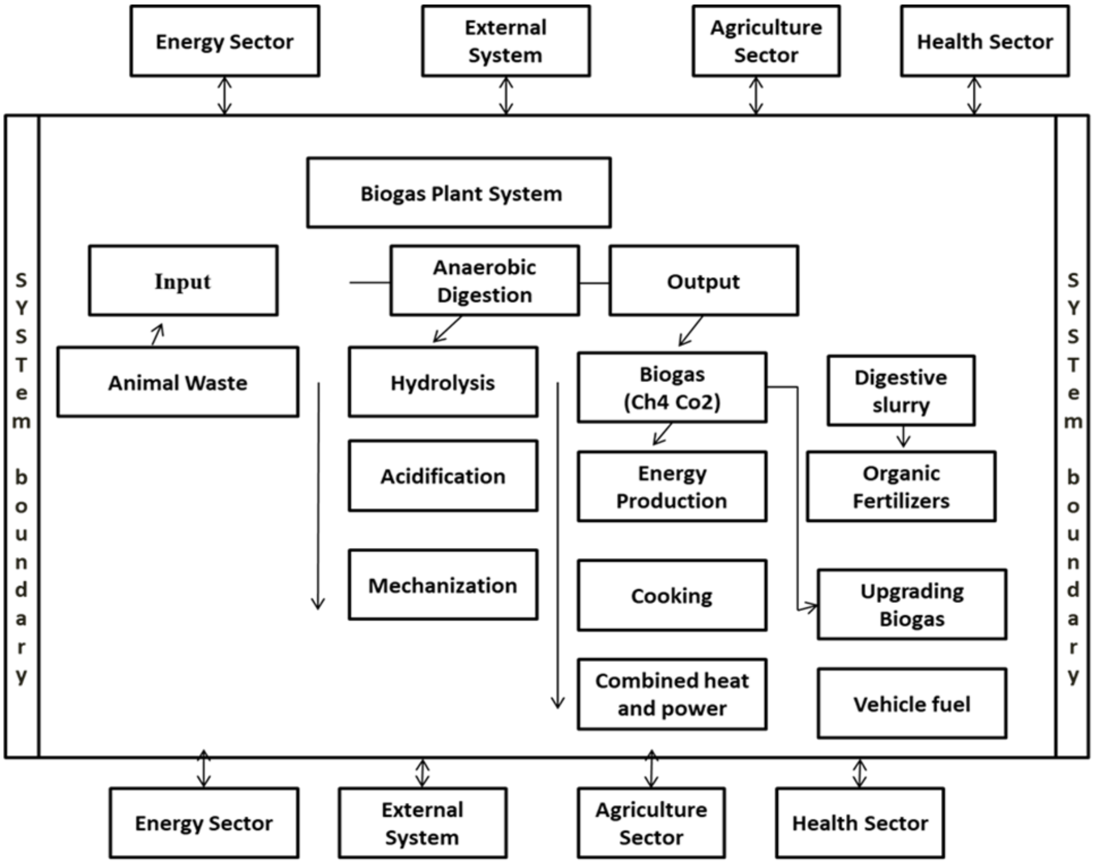


FIGURE 3.2: Conceptual framework of biogas plant

be provided in the following section. This conceptual framework is developed to investigate two key aspects.

1. How various stakeholders benefit from biogas and how this contributes to the sustainable development of the city.
2. How stakeholders such as the government, community, and financial institutions contribute to the advancement of biogas technology.

3.4 Data Collection

To estimate the total waste associated with biogas production potential, the research required data on the total number of animals categorized by type. The Ministry of Livestock & Development Department in Punjab, Pakistan, provided the data on the population of animals. The population of livestock and the quantity of poultry and animals in Punjab from 2013 to 2023 were among the data gathered.

Table 3.1: Total live Stock population (millions) in Punjab from 2013 to 2023

Year	Category - I		Category - II		Category-III	Category-IV
	Cow	Buffalo	Sheep	Goat	Camels/Horse, Donkey	Poultry form
2013	5.17	4.77	8.63	2.38	37.24	526.82
2014	6.04	5.99	8.05	3.42	39.67	574.94
2015	7.93	7.52	7.52	4.92	42.25	631.73
2016	9.81	9.45	7.01	7.07	45.01	690.83
2017	12.15	11.87	6.55	10.18	47.94	755.88
2018	15.05	14.91	6.11	14.64	51.07	828.16
2019	18.63	18.73	5.07	21.06	54.04	910.04
2020	23.07	23.53	5.32	30.30	57.95	1001.72
2021	28.56	29.56	4.96	43.58	61.73	1100.37
2022	35.37	37.13	4.63	62.69	65.75	1214.61
2023	43.79	46.64	4.32	90.18	70.04	1338.88

3.5 Total Number of Animals

According to the data from 2023, the total population included 43.8 million cattle, 46.6 million buffalo, 4.3 million sheep, 90.18 million goats, 70 million camels, horses, and donkeys, and 1.34 billion poultry. This data is mentioned below:-

Table 3.2: Total Livestock Produced in Punjab in 2023

Categories	Animal	Yearly Population, (Millions)
Category-1	Cow	43.79
	Buffalo	46.64
Category-2	Sheep	4.32
	Goat	90.18
Category-3	Camel, Horse & Donkey	70.04
Category-4	Poultry	1338.882

3.6 Total Livestock Waste Generation Rate in Punjab

Organic materials used in biogas production include livestock and poultry waste. Furthermore, the amount of manure is determined based on the population of livestock and poultry, as shown in the table above.

To calculate the volume of waste, we have categorized all types of livestock into four groups for simplicity:

- Category 1 (Cat-1): Cow and Buffalo
- Category 2 (Cat-2): Sheep and Goat
- Category 3 (Cat-3): Camel, Horse, and Donkey
- Category 4 (Cat-4): Poultry

The manure calculation is done by using following formula [101].

$$TCM = \sum NAi \times UMPi \times CRi \tag{3.1}$$

Where:

TCM= Total Collectable manure for all types of animal (Tons/Year)
NAi= Number of animals
UMPi= Unit Manure potential
CRi= Collective ratio

3.7 Calculation of Biogas Output Capacity from the Estimated Waste

Factors such as livestock weight and the feed availability coefficient are considered when calculating the biogas production potential from the available livestock, which is categorized into four groups. The weight of the animals is important because it influences their metabolic rate, the amount of feed they consume, and ultimately the amount of manure they produce, which is used for biogas generation. This coefficient accounts for the availability and quality of feed for the livestock. The better the quality and quantity of feed, the higher the manure production, which in turn can affect biogas production.

The livestock is divided into four categories, likely based on species and size, to simplify calculations and better estimate biogas production for different types of animals. Table 3.3 the range of total solids in animal waste and the resulting biogas production are calculated based on the amount of total solids present. The range of total solids in animal waste and the resulting biogas production are calculated based on the amount of total solids present

Table 3.3: Percentage of total solids in animal waste and biogas production

Livestock	TS (%)	Biogas(m^3/Kg TS)	Average Value
Cattle Manure (Fresh)	25-30	0.6-0.8	0.7
Sheep Manure (Fresh)	18-25	0.3-0.4	0.35
Poultry Manure	10-29	0.3-0.8	0.55

It is estimated that the Total Solids (TS) content in the manure of category-1, category-2, and category-3 animals is 25%, while the TS content in poultry manure is 29%. Theoretical Biogas Production Potential, Bp (m^3/year) [65]

$$Bp = TCM \times Ts \times SMYi \tag{3.2}$$

where:

Bp=Bio Gas Production

TCM= Total collectable manure for all type of animal

TS=Total solid animal

SMYi= Specific methane yield of manure for animal

3.8 Estimation of Methane and its Potential for Conversion into Electricity

Methane typically constitutes 60-70% of the total biogas volume, though this percentage can vary based on the type of manure or source [103]. The estimated methane composition for Cat-1, Cat-2, Cat-3, and Cat-4 manure ranges from 50-70%, 40-50%, 50-60%, and 50-70%, respectively.

For calculation purposes, the methane content is considered to be 60% for Cat-1 manure, 45% for Cat-2 manure, 50% for Cat-3 manure, and 60% for Cat-4 manure. The quantity of electricity generation is calculated using equation.

$$QE = LCVm \times CH_4 \times Bp \times \eta \tag{3.3}$$

where:

QE = Quantity of electricity generation

LCVm=Lower Calorific value of Methane

CH_4=Methane percent in biogas for livestock type

BP=Biogas production for the livestock type

η=Overall efficiency of conversion of biogas to electricity for small generation system [104]

LCVm represents the lower calorific value of methane, which is considered to be 6 kWh per cubic meter of methane [105].

CH_4 indicates the percentage of methane in biogas for Cat-1, which is 60%

eta represents the overall efficiency of biogas conversion, with an assumed value of 30% (efficiency of heat-to-electricity conversion) [106].

3.9 Estimation of Bio-Fertilizers Yield

Approximately 60% of volatile solids (VS) are converted into biogas, which also holds potential as a bio-fertilizer [107]. The volatile solids in various organic wastes decrease by 40–46% after 80 days in the anaerobic digester [108]. The research used 40% of the dry matter remaining in the treatment plant as the percentage of volatile solids [104]. The below equation was used to estimate the bio- fertilizer yields:

$$(Bio - fertilizeryield)BFY = (DM - VS) + 40\%(VS) \tag{3.4}$$

Where:

BFY = Bio-fertilizer yield,

DM = Dry mass

VS = Volatile solids.

3.9.1 Calculation of Category-I

3.9.1.1 Manure Collection

In 2023, to calculate the volume of waste for Category 1 (Cows & Buffaloes), we use the formula provided below. The waste is measured in tons per year. It is assumed that each cow and buffalo produces an average of 23 kg of manure per day, and the manure collection rate is 50% [101].

$$TCM = \sum NAi \times UMPi \times Cri = 90.43 \times 10^6 \times 23 \times 0.5 \times 365 \tag{3.5}$$

$$TCM = 3.80 \times 10^8 Tons/Year \tag{3.6}$$

3.9.1.2 Biogas Production

TS in manure refers to the solid matter remaining after the moisture in manure is removed. The higher the TS content, the greater the proportion of solid material available for biogas production. Cat-1 (cows, buffaloes)have a TS content of 25%. This means that 25% of the manure's weight is made up of solid material, which is available for biogas production.The biogas yield refers to the volume of biogas produced per unit of TS content in the manure. The yield is affected by factors such as the type of manure, the feed given to the animals, and the conditions of the anaerobic digestion process. Cat-1 produces 0.6 m^3 of biogas per kg of TS for 2023. Theoretical Biogas Production Potential, Bp (m^3/year)

$$\begin{aligned} Bp &= TCM \times Ts \times SMYi \\ &= 3.80 \times 10^{11} \times 0.25 \times 0.70 \\ Bp &= 6.64 \times 10^{10} m^3 CH_4/Year \end{aligned}$$

3.9.1.3 Electricity Generation

The methane composition derived from the manure of Category 1 (Cat-1) livestock, which includes cows and buffaloes, is estimated to range between 50% and 70%. In 2023, the average methane content is considered to be 60% for the manure from these animals.

$$\begin{aligned} QE &= LCVm \times CH_4 \times Bp \times \eta = 6 \times 0.6 \times 6.64 \times 10^{10} \times 0.3 \\ &= 7.17 \times 10^{10} KWh/Year \\ QE &= 7.17 \times 107 MWh/Year \end{aligned}$$

3.9.1.4 Bio-Fertilizer

Approximately 60% of volatile solids (VS) are transformed into biogas, which also has the potential to be used as a bio-fertilizer [107]. The volatile solids in various organic wastes decrease by 40–46% after 80 days in the anaerobic digester [108]. In the research, the volatile solids percentage was 40% of the dry matter remaining in the treatment plant [104]; Equation below was used to estimate the bio fertilizer yields:

$$(Biofertilizeryield) BFY = (DM - VS) + 40\%(VS)$$

Where:

BFY = Bio fertilizer yield,

DM = Dry mass

VS = Volatile solids.

$$\begin{aligned} DM &= 3.80 \times 10^8 \times 0.15 & &= 5.70 \times 10^7 Tons \\ VS &= 96.7\% of DM & &= 0.967 \times 5.70 \times 10^7 \\ VS &= 5.51 \times 10^7 Tons/Year & & \end{aligned}$$

The dry matter constitutes 15% of the manure, amounting to 5.70 × 10^7 tons [117].

The volatile solids make up 96.7% of the dry matter, totaling 5.51 × 10^7 tons per year. Hence to determine the bio fertilizer yield.

$$\begin{aligned} BFY &= (5.70 \times 10^7 - 5.51 \times 10^7) + 0.4(5.51 \times 10^7) \\ &= 1.9 \times 10^6 + 2.20 \times 10^7 \\ Total BFY &= 2.39 \times 10^7 Tons/year \\ One\ tone\ BFY\ Price &= Rs.3600 \\ 2.39\ \times\ 10^7\ tons\ BFY\ Price &= 3600 \times 23.9 \times 10^6 \end{aligned}$$

Saving Amount Rs. 86184 Million

3.9.1.5 GHG Emission

Biogas combustion for power generation can replace fossil fuels, thereby lowering carbon emissions into the atmosphere. In this study, gasoline was chosen as a comparison since it is widely used by energy consumers in Punjab for daily activities, including fueling vehicles and generators. The use of biogas in place of gasoline will help reduce CO_2 emissions. Equation [109] It can be used to estimate the reduction in CO_2 emissions by substituting gasoline fuel with biogas.

CO_2 Emission 1 m^3 Biogas = 9.2 kg CO_2/m^3 In Air [102]

The emission value generated from burning biogas will be 1.96 kg CO_2/ m^3 biogas

Note: 1 m^3 Gas converted into LPG then equal to 3.7 Liter

1 m^3 of Biogas (60%) = $3.7 \times 0.6 = 2.22$ Liter

1 m^3 of Biogas (60%) = 2.22 Liter

1 m^3 Biogas = 1.96 Kg CO_2

2.22 liter = 1 m^3 = 1.96 Kg CO_2(one liter = 1/ 2.22 m^3)

One liter Biogas = 1.96/2.22 = 0.88 Kg CO_2

One liter Biogas (60%) = 0.88 Kg CO_2

6.64×10^{10} m^3 = $2.22 \times 6.64 \times 10^{10}$ liter = 1.47×10^{11}liter

1.47×10^{11}liter = $0.88 \times 1.47 \times 10^{11}$Kg CO_2 = 1.30×10^{11}Kg CO_2 = 1.30×10^{8} tons CO_2/year

Reduction of greenhouse gas emissions by substituting gasoline (petrol) with biogas. Comparison of Biogas and Petrol regarding GHG Emission

1 Liter Petrol = 2.3 Kg CO_2 [116]

1.47×10^{11}liter Biogas = 1.47×10^{11} liter Petrol

1.47×10^{11}Liter Petrol = $2.3 \times 1.47 \times 10^{11}$Kg CO_2

1.47×10^{11}Liter Petrol = 3.39×10^{10}Kg CO_2 = 3.39×10^{8} tons CO_2/year

GHG Reduction=GHG Emission (Petrol) – GHG Emission (Biogas)

= 3.39×10^{8} tons CO_2/year - 1.30×10^{8} tons CO_2/year

GHG Reduction= 209 Million Tons CO_2/year

TABLE 3.4: Estimation of Manure, Biogas Potential, Electricity Generation and GHG Emission from Buffalo & Cattle

Category - I				Manure	Biogas	Electricity	Bio-Fertilizer	GHG Emission (Biogas)	GHG Emission (Petrol)	GHG Reduction
Year	Cattle(M)	Buffalo(M)	Sum	M.Tons/year	M.m^3/year	TWh/year	M.Tons/year	M.Tons CO$_2$/year	M.Tons CO$_2$/year	M.Tons CO$_2$/ year
2013	5.17	4.77	9.94	41.72	7301.55	7.89	2.63	14.26	37.28	23.02
2014	6.04	5.99	12.03	50.50	8836.79	9.54	3.18	17.26	45.12	27.86
2015	7.93	7.52	15.45	64.85	11348.99	12.26	4.08	22.17	57.95	35.78
2016	9.81	9.45	19.26	80.84	14147.67	15.28	5.09	27.64	72.24	44.60
2017	12.15	11.87	24.02	100.82	17644.19	19.06	6.35	34.47	90.09	55.62
2018	15.05	14.91	29.96	125.76	22007.49	23.77	7.92	42.99	112.37	69.38
2019	18.63	18.73	37.36	156.82	27443.26	29.64	9.87	53.61	140.13	86.51
2020	23.07	23.53	46.60	195.60	34230.61	36.97	12.32	66.87	174.78	107.91
2021	28.56	29.56	58.12	243.96	42692.77	46.11	15.36	83.40	217.99	134.58
2022	35.37	37.13	72.50	304.32	53255.78	57.52	19.16	104.04	271.92	167.88
2023	43.79	46.64	90.43	379.58	66426.49	71.74	23.90	129.77	339.17	209.40
Total	205.57	210.10	415.67	1744.77	305335.59	329.76	109.87	596.50	1559.04	962.54

3.9.2 Calculation of Category-II

3.9.2.1 Manure Collection

To calculate the volume of waste for Category 1 (Sheep and Goat), we use the formula provided below. The waste is measured in tons per year. It is assumed that Sheep and Goat produces an average of 2 kg of manure per day, and the manure collection rate is 50% [110].

$\mathrm{TCM} = \sum \mathrm{NAi} \times \mathrm{UMPi} \times \mathrm{Cri} = 94.5 \times 10^{6} \times 02 \times 0.5 \times 365 = 3.45 \times 10^{7}$ Tons/Year

3.9.2.2 Biogas Production

TS in manure refers to the solid matter remaining after the moisture in manure is removed. The higher the TS content, the greater the proportion of solid material available for biogas production. Cat-2 (sheep, goats) have a TS content of 25%. This means that 25% of the manure's weight is made up of solid material, which is available for biogas production. The biogas yield refers to the volume of biogas produced per unit of TS content in the manure. The biogas yield is affected by factors such as the type of manure, the feed given to the animals, and the conditions of the anaerobic digestion process. In 2023, Cat-2 generated 0.4 m^3 of biogas per kilogram of total solids (TS).

Theoretical Biogas Production Potential, Bp (m^3/year)

$\mathrm{Bp} = \mathrm{TCM} \times \mathrm{Ts} \times \mathrm{SMYi} = 3.45 \times 10^{7} \times 0.25 \times 0.35$ $\mathrm{Bp} = 3.02 \times 10^{9}\ \mathrm{m}^3\ \mathrm{CH}_4/\mathrm{Year}$

3.9.2.3 Electricity Generation

The methane composition derived from the manure of Category-II livestock, which includes Sheep and Goats, is estimated to range between 40% and 50%. The average methane content is to be 30% for the manure from these animals in 2023 [111].

$QE = LCVm \times CH_4 \times Bp \times \eta = 6 \times 0.3 \times 3.02 \times 10^9 \times 0.3 = 1.63 \times 10^9$KWh /Year

QE=3.83 × 106 MWh /Year

3.9.2.4 Bio-Fertilizer

Approximately 60% of volatile solids (VS) are transformed into biogas, which also has the potential to be used as a bio-fertilizer [23]. The volatile solids in various organic wastes decrease by 40–46% after 80 days in the anaerobic digester. In the research, the volatile solids percentage was 40% of the dry matter remaining in the treatment plant [104]. The equation [112] below was used to estimate the bio fertilizer yields

(Bio fertilizer yield) BFY= (DM - VS) + 40% (VS)

where:
BFY = Bio fertilizer yield,
DM = Dry mass
VS=Volatile solids

$DM = 3.45\times 10^7 \times 0.15 = 5.17 \times 10^6$ Tons

VS=96.7% of DM = $0.967 \times 5.17 \times 10^6 = 5 \times 10^6$ Tons /Year

The dry matter constitutes 15% of the manure, amounting to 5.17×10^6 Tons/year

The volatile solids make up 96.7% of the dry matter, totaling 5×10^6 Tons /Year

Hence to determine the bio fertilizer yield

$BFY = (5.17 \times 10^6 - 5 \times 10^6) + 0.4\,(5 \times 10^6) = 2.17 \times 10^6$ Tons/year

Total. $BFY = 2.17 \times 10^6$ Tons/year

One tone BFY Price = Rs. 3600 BFY Price = $3600 \times 2.17 \times 10^6$

Saving Amount Rs.7812 Million

3.9.2.5 GHG Emission

Carbon emissions into the environment can be decreased by using biogas combustion to generate electricity instead of fossil fuels. Gasoline was chosen for this study because it is a fossil fuel that more Punjabi energy customers use on a regular basis for both their cars and generators. Utilizing biogas will lower carbon dioxide emissions. Equation [113] can be used to estimate the reduction in CO_2 emissions by substituting gasoline fuel with biogas.

Note: 1 m^3 Gas converted into LPG then equal to 3.7 Liter [113]

1 m^3 of Biogas (60%) = $3.7 \times 0.6 = 2.22$ Liter

1 m^3 of Biogas (60%) = 2.22 Liter

1 m^3 Biogas = 1.96 Kg CO_2

2.22 liter = 1 m^3 = 1.96 Kg CO_2 (one liter = 1/ 2.22 m^3)

One liter Biogas = 1.96/2.22 = 0.88 Kg CO_2

3.02×10^9 m^3 = $2.22 \times 3.02 \times 10^9$ liter = 6.70×10^9 liter

6.70×10^9 liter = $0.88 \times 6.70 \times 10^9$ Kg CO_2 = 5.90×109 Kg CO_2= 5.90×10^6 Tons CO_2/year

GHG emissions can be reduced by replacing biogas with gasoline (petrol)

Comparison of Biogas and Petrol regarding GHG Emission

1 Liter Petrol = 2.3 Kg CO_2

6.70×10^9liter Biogas = 6.70×10^9liter Petrol

6.70×10^9Liter Petrol = $6.70 \times 10^9 \times 2.30$ Kg CO_2

6.70×10^9Liter Petrol =1.54×10^{10} Kg CO_2 = 1.54×10^7 Tons CO_2/year

GHG Emission Reduction = GHG Emission (Petrol) – GHG Emission (Biogas)

= 1.54×10^7 - 5.90×10^6= 9.51 million tons CO_2/year

Hence the avoid CO_2 was estimated as (9.51×10^6 Tons CO_2/year) by using biogas Generator as compare to Petrol Generator for all types of animal wastes. Reduction in carbon footprint by using biogas approximates 72%.

Table 3.5: Estimation of Manure, Biogas Potential, Electricity Generation and GHG Emission from Sheep and Goat

Category - II				Manure	Biogas	Electricity	Bio-Fertilizer	GHG Emission	GHG Emission (Petrol)	GHG Reduction
Year	SheepM(M)	Goat(M)	Sum	M.Tons/year	m^3/year	TWh/year	M.Tons/year	M.Tons CO_2/year	M.Tons CO_2/year	MTons CO_2/year
2013	8.63	2.38	11.01	4.02	351.63	0.19	0.25	0.69	1.80	1.11
2014	8.05	3.42	11.47	4.19	366.32	0.20	0.26	0.72	1.87	1.15
2015	7.52	4.92	12.44	4.54	397.30	0.21	0.29	0.78	2.03	1.25
2016	7.01	7.07	14.08	5.14	449.68	0.24	0.32	0.88	2.30	1.42
2017	6.55	10.18	16.73	6.11	534.31	0.29	0.38	1.04	2.73	1.68
2018	6.11	14.64	20.75	7.57	662.70	0.36	0.48	1.29	3.38	2.09
2019	5.07	21.06	26.13	9.54	834.53	0.45	0.60	1.63	4.26	2.63
2020	5.32	30.30	35.62	13.00	1137.61	0.61	0.82	2.22	5.81	3.59
2021	4.96	43.58	48.54	17.72	1550.25	0.84	1.12	3.03	7.92	4.89
2022	4.63	62.69	67.32	24.57	2150.03	1.16	1.55	4.20	10.98	6.78
2023	4.32	90.18	94.50	34.49	3018.09	1.63	2.17	5.90	15.41	9.51
Total	68.17	290.42	358.59	130.89	11452.47	6.18	8.24	22.37	58.48	36.10

3.9.3 Calculation of Manure of Category-III

3.9.3.1 Manure Collection

To calculate the volume of waste for Category-III (Camel, Horse, and Donkey), we use the formula provided below. The waste is measured in tons per year. It is assumed that each camel, horse and donkey produces an average of 16 kg of manure per day, and the manure collection rate is 33% [114].

$\mathrm{TCM} = \sum \mathrm{NAi} \times \mathrm{UMPi} \times \mathrm{Cri} = 7.0 \times 10^7 \times 16 \times 0.33 \times 365$

$\mathrm{TCM} = 1.35 \times 10^8$ Tons/Year

3.9.3.2 Biogas Production

TS in manure refers to the solid matter remaining after the moisture in manure is removed. The higher the TS content, the greater the proportion of solid material available for biogas production. Cat-3 (Camels, Horses, Donkeys) have a TS content of 25%. This means that 25% of the manure's weight is made up of solid material, which is available for biogas production. The biogas yield refers to the volume of biogas produced per unit of TS content in the manure. A number of variables, including the kind of dung, the animal feed, and the anaerobic digestion process's parameters, affect the production. For every kilogram of TS, Cat-3 generates 0.4 m^3 of biogas.

Theoretical Biogas Production Potential, Bp (m^3 year)

$\mathrm{Bp} = \mathrm{TCM\ x\ Ts\ x\ SMYi} = 1.35 \text{ x } 10^8 \text{ x } 0.25 \text{ x } 0.4 = 1.35 \text{ x } 10^{10}\ m^3\ CH_4/\mathrm{Year}$

3.9.3.3 Electricity Generation

The methane composition derived from the manure of Category-3 livestock, which includes camels, horses and monkey are estimated to range between 50% and 60%. The average methane content is considered to be 40% for the manure from these animals (Cat-3).

QE = LCVmx CH_4 x Bp x η = 6 x 0.4 x 1.35 x 10^{10}x 0.3 = 9.72 x 10^9KWh /Year

QE = 9.72 x 10^6 MWh /Year

3.9.3.4 Bio-fertilizer

Approximately 60% of volatile solids (VS) are transformed into biogas, which also has the potential to be used as a bio-fertilizer [23]. The volatile solids in various organic wastes decrease by 40–46% after 80 days in the anaerobic digester. In the research, the volatile solids percentage was 40% of the dry matter remaining in the treatment plant [104], Equation [112] below was used to estimate the bio fertilizer yields.

(Bio fertilizer yield) BFY=(DM - VS)+40%(VS)

Where:
BFY = Bio fertilizer yield,
DM = Dry mass
VS = Volatile solids

DM = 1.35 x 10^8x 0.15

=2.02 x 10^7 Tons/year

VS=96.7% of DM

=0.967 x 2.02 x 10^7

=1.96 x 10^7 Tons /Year

The dry matter constitutes 15% of the manure, amounting to 2.02 x 10^7 Tons/year

The volatile solids make up 96.7% of the dry matter, totaling 1.96 x 10^7Tons /Year

Hence to determine the bio fertilizer yield

BFY = (2.02 x 10^7– 1.96 x 10^7) + 0.4 (1.96 x 10^7)

= 0.06 x 10^7 + 0.784 x 10^7

= 8.50 x 10^6 Tons/year

Total. BFY = 8.50 x 10^6Tons/year

One tone BFY Price = Rs. 3600

BFY Price = 3600 x 8.50 x 10^6

Saving Amount = Rs.30600 Million

3.9.3.5 GHG Emission

Biogas combustion offers a potential pathway to replace fossil fuels like gasoline, thereby mitigating carbon emissions. In this study, gasoline was chosen as a comparison since it is widely used by energy consumers in Punjab for daily activities, including fueling vehicles and generators. The use of biogas in place of gasoline will help reduce CO_2 emissions. Equation [109] was used to calculate the CO_2 emission minimizes by replacing gasoline fuel with biogas.

Note: 1 m^3 Gas converted into LPG then equal to 3.7 Liter

1 m^3 of Biogas (60%) = 3.7 × 0.6 = 2.22 Liter

1 m^3 of Biogas (60%) = 2.22 Liter

1 m^3 Biogas = 1.96 Kg CO_2

2.22 liter = 1 m^3 = 1.96 Kg CO_2 (one liter = 1/ 2.22 m^3)

One liter Biogas = 1.96/2.22 = 0.88 Kg CO_2

1.35 x 10^{10} CH_4 m^3 = 2.22 x 1.35 x 10^{10} liter = 3 x 10^{10} liter

3 x 10^{10} liter = 0.88 x 3 x 10^{10} Kg CO_2 = 2.64 x 10^{10} Kg CO_2 = 2.64 x 10^7 Tons CO_2/year

Comparison of Biogas and Petrol regarding GHG Emission

1 Liter Petrol = 2.3 Kg CO_2

3 x 10^{10}liter Biogas = 3 x 10^{10}liter Petrol

3 x 10^{10}Liter Petrol = 3 x 10^{10}x2.3 Kg CO_2

3 x 10^{10}Liter Petrol = 6.9 x 10^{10} Kg CO_2/year= 6.9 x 10^7 Tons CO_2 /year

Difference = 1.17 x 10^5 tons CO_2/year

GHG Emission Reduction = GHG Emission (Petrol) – GHG Emission (Biogas)

= 6.9 x 10^7 – 2.64 x 10^7= 42.6 million tons CO_2/year

Hence the avoid CO_2 was estimated as (42.6 million tons CO_2/year) by using biogas Generator as compare to Petrol Generator for all types of animal wastes. Reduction in carbon footprint by using biogas approximates 72%.

3.9.4 Calculation of Manure of Category-IV

3.9.4.1 Manure Collection

To calculate the volume of waste for Category-IV (Poultry), we use the formula provided below. The waste is measured in tons per year. It is assumed that poultry produces an average of 0.05 kg of manure per day, and the manure collection rate is 99% [115].

TCM= $\sum$ NAi x UMPi x Cri = 1338.882 x 0.99 x 0.05 x 365

TCM = 2.42 x 10^7 Tons/Year

3.9.4.2 Biogas Production

TS in manure refers to the solid matter remaining after the moisture in manure is removed. Higher total solids (TS) content increases the proportion of solid material available for biogas production. Cat-4 (Poultry) has a TS content of 25%. This means that 25% of the manure's weight is made up of solid material, which is available for biogas production.

Table 3.6: Estimation of Manure, Biogas Potential, Electricity Generation and GHG Emission from Camels/Horse and Donkey

Category - III		Manure	Biogas	Electricity	Bio-Fertilizer	GHG Emission(Biogas)	GHG Emission (Petrol)	GHG Reduction
Year	Camels / Horse, Donkey	M.Tons/year	m^3/year	TWh/year	M.Tons/year	M.Tons CO_2/year	M.Tons CO_2/year	M.Tons CO_2/year
2013	37.24	71.77	7176.89	5.17	4.52	14.02	36.65	22.62
2014	39.67	76.45	7645.20	5.50	4.81	14.94	39.04	24.10
2015	42.25	81.42	8142.42	5.86	5.13	15.91	41.58	25.67
2016	45.01	86.74	8674.33	6.25	5.46	16.95	44.29	27.34
2017	47.94	92.39	9239.00	6.65	5.82	18.05	47.17	29.13
2018	51.07	98.42	9842.21	7.09	6.20	19.23	50.25	31.03
2019	54.04	104.15	10414.59	7.50	6.56	20.35	53.18	32.83
2020	57.95	111.68	11168.12	8.04	7.03	21.82	57.02	35.21
2021	61.73	118.97	11896.61	8.57	7.49	23.24	60.74	37.50
2022	65.75	126.71	12671.34	9.12	7.98	24.75	64.70	39.95
2023	70.04	134.98	13498.11	9.72	8.50	26.37	68.92	42.55
Total	572.69	1103.69	110368.82	79.47	69.50	215.62	563.54	347.93

The biogas yield refers to the volume of biogas produced per unit of TS content in the manure. The kind of manure, the animal diet, and the circumstances surrounding the anaerobic digestion process all affect the production. Cat-4 produces 0.8 m^3 of biogas per kg of TS.

Theoretical Biogas Production Potential, Bp (m^3/year)

$Bp = TCM \text{ x } Ts \text{ x } SMYi = 2.42 \text{ x } 10^{10} \text{ x } 0.25 \text{ x } 0.55$

$Bp = 3.33 \text{ x } 10^9 \text{ m}^3 \text{ CH}_4\text{/Year}$

3.9.4.3 Electricity Generation

The methane composition derived from the manure of Category 4 (Cat-4) livestock, which includes poultry is estimated to range between 50% and 70%. The average methane content is considered to be 60% for the manure from these animals (Cat-4).

$QE = LCVm \text{ x } CH_4 \text{ x } Bp \text{ x } \eta = 6 \text{ x } 0.6 \text{ x } 3.33 \text{ x } 10^9 \text{ x } 0.3 = 3.59 \text{ x } 10^9$ KWh /Year

$QE = 3.59 \text{ x } 10^6$ MWh /Year

3.9.4.4 Bio-fertilizer

Biogas, which has the potential to be used as biofertilizer, is produced from around 60% of volatile solids (VS). [23]. The volatile solids in various organic wastes decrease by 40–46% after 80 days in the anaerobic digest. In the research, the volatile solids percentage was 40% of the dry matter remaining in the treatment plant [104]. The equation [112] below was used to estimate the bio fertilizer yields

(Bio fertilizer yield) BFY=(DM - VS)+40%(VS)

Where:
BFY = Bio fertilizer yield,
DM=Dry-mass
VS=Volatile Solid

DM = 2.42 x 10^7x 0.15 = 3.63 x 10^6 Tons/year

VS=96.7% of DM =0.967 x 3.63 x 10^6 = 3.51 x 10^6 Tons /Year

The dry matter constitutes 15% of the manure, amounting to 3.63 x 10^6Tons/year

The volatile solids make up 96.7% of the dry matter, totaling 3.51 x 10^6 Tons /Year

Hence to determine the bio fertilizer yield

BFY = (3.63 x 10^6 – 3.51 x 10^6) + 0.4 (3.51 x 10^6) = 0.12 x 10^6+ 1.40 x 10^6

= 1.52 x 10^6 Tons/year Total. BFY = 1.52 x 10^6Tons/year

One tone BFY Price = Rs. 3600 BFY Price = 3600 x1.52 x 10^6

Saving Amount Rs. 5486.4 Million

3.9.4.5 GHG Emission

Biogas combustion for power generation can replace fossil fuels, thereby lowering carbon emissions into the atmosphere. In this study, gasoline was chosen as a comparison since it is widely used by energy consumers in Punjab for daily activities, including fueling vehicles and generators. The use of biogas in place of gasoline will help reduce CO_2 emissions. Equation [109] can be used to estimate the reduction in CO_2 emissions by substituting gasoline fuel with biogas.

Note: 1 m^3 Gas converted into LPG then equal to 3.7 Liter

1 m^3 of Biogas (60%) = 3.7 × 0.6 = 2.22 Liter

1 m^3 of Biogas (60%) = 2.22 Liter

1 m^3 Biogas = 1.96 Kg CO_2

2.22 liter = 1 m^3 = 1.96 Kg CO_2 (one liter = 1/ 2.22 m^3)

One liter Biogas = 1.96/2.22 = 0.88 Kg CO_2

3.33 x 10^9 m^3 = 2.22 x 3.33 x 10^9 liter = 7.39 x 10^9 liter

7.39 x 10^9liter = 0.88 x 7.39 x 10^9Kg CO_2 = 6.5 x 10^9Kg CO_2= 6.5 x 10^6 Tons CO_2/year

Comparison of Biogas and Petrol regarding GHG Emission

1 Liter Petrol = 2.3 Kg CO_2

7.39 x 10^9liter Biogas = 7.39 x 10^9liter Petrol

7.39 x 10^9Liter Petrol = 7.39 x 10^9x 2.3 Kg CO_2

7.39×10^9 Liter Petrol = 1.7×10^{10} Kg CO_2/year

Difference = 1.7×10^{10} Kg CO_2 = 1.7×10^7 tons CO_2/year

GHG Emission Reduction = GHG Emission (Petrol) – GHG Emission (Biogas)

= $1.7 \times 10^7 - 6.5 \times 10^6$ = 10.49 million tons CO_2/year

Hence the avoid CO_2 was estimated as (10.49 million tons CO_2/year) by using biogas Generator as compare to Petrol Generator for all types of animal wastes. Reduction in carbon footprint by using biogas approximates 72%.

TABLE 3.7: Estimation of Manure, Biogas Potential, Electricity Generation and GHG Emission from Poultry

Category - IV		Manure	Biogas	Electricity	Bio-Fertilizer	GHG Emission(Biogas)	GHG Emission (Petrol)	GHG Reduction
Year	Poultry Form	M.Tons/year	m^3/year	TWh/year	M.Tons/year	M.Tons CO_2/year	M.Tons CO_2/year	M.Tons CO_2/ year
2013	526.83	9.52	1308.79	1.88	0.60	2.56	6.68	4.13
2014	574.94	10.39	1428.31	2.06	0.65	2.79	7.29	4.50
2015	631.73	11.41	1569.40	2.26	0.72	3.07	8.01	4.95
2016	690.83	12.48	1716.22	2.47	0.79	3.35	8.76	5.41
2017	755.88	13.66	1877.82	2.70	0.86	3.67	9.59	5.92
2018	828.17	14.96	2057.40	2.96	0.94	4.02	10.51	6.49
2019	910.04	16.44	2260.79	3.26	1.04	4.42	11.54	7.13
2020	1001.72	18.10	2488.55	3.58	1.14	4.86	12.71	7.84
2021	1100.37	19.88	2733.62	3.94	1.25	5.34	13.96	8.62
2022	1214.61	21.95	3017.44	4.35	1.38	5.89	15.41	9.51
2023	1338.88	24.19	3326.16	4.79	1.52	6.50	16.98	10.49
Total	9573.99	172.98	23784.49	34.25	10.89	46.47	121.44	74.98

3.10 Materials Required for Constructing a Fixed-dome Biogas Plant with a Capacity of 50 m^3.

Table 3.8: Rough Cost Estimate for Biogas Plant 50 m^3 at KIT

Sr.	SINO	DESCRIPTION	QTY	UNIT	*RATE	AMOUNT
1	01-02	Excavation in hard soil up to a depth of 1.5 meters for foundations and pipe trenches up to 1.5 meters wide, as well as for shafts, wells, and independent holes up to 30 square meters each. The excavated earth will be cleared up to 10 meters from the edges. Timbering will be charged separately, and trenches exceeding 1.5 meters in width will be considered as surface areas.	118	Cum	429	50,622
2	NSR	Local Gahra 6 " thick, in bed of Digester	7.9	Cum	2,912	23,007
3	03-03	PCC 1:3:6, all as specified.	7.9	Cum	12,698	100,317
4	04-22	The 115 mm thick burned brick work in the wall was laid and joined in cement mortar 1:3 either straight or curved, with an inner radius of 6 m and a depth of 4.25 m.	12.74	Cum	21,803	277,771
5	3-5	Providing and laying of PCC with 3000 psi compressive cylindrical strength in all non- structural elements except formwork. (for Segmental Dome)	18.55	Cum	14,721	273,080

Continued to next page

Table 3.8 continued from previous page

Sr.	SINO	DESCRIPTION	QTY	UNIT	*RATE	AMOUNT
6	3-9	Rack Beam 10"x18"x22": Rate same as item 3-7 but in roof slabs, landings, walls, plinth beams and bands etc. all as specified including form work (reinforcement measured and paid separately).	0.77	Cum	22,353	17,211
7	13-3	Cement Plaster 1:3, 13 mm thick finished as specified (Basement, GF, FF and 2nd floor). 2 Layers inside dome.	146.29	Sqm	561	82,069
8	22-4	Providing and laying a precast RCC slab, length 1.524 M to 1.981 M, width 0.304 M, with hoisting, setting, and jointing in CM (1:4) as indicated.	9.66	Sqm	4,102	39,624
9	22-5	Providing and laying, Precast pre-stressed, RCC girders size 102 mm x 228 mm, including setting and hoisting, all as specified for span 2.438 M to 4.877 M.	6	m	2,152	12,910
10	28-293	UPVC soil and waste pipe, 200 mm.	3.65	m	1,998	7,293
11	NSR	Turret around GI pipe width 10"x height 10"	1	No	8,250	8,250
					Sum	892,155
				Contingencies 10%		89,216
				Total Rs.		981,371

*Rates of items are according to MES schedule 2021, with premium 65%

Note: Estimated cost is without Taxes.

Total cost of biogas plant = Rs 120000 (Along with operational Charges)

QE = LCVm x CH_4 x Bp x η

= 6 x 50 x 0.6 x 0.3

= 45 KWh

Life Span = 20 years

Rs per year = 1200000/20 = 60,000 Rs

Total unit per year = 45 x 365 = 16425 KWh

Rate per unit = 60,000/16425 = 3.67 = 4.00 Rs

Bio-fertilizer (By-product) = 40 Kg/Day

Amount per Rs. 15/Kg

Total Saving = 40 x 15 = 600 Rs

3.11 Estimation of Solar Installation Capacity 12 KWh

The estimation of solar installation capacity is crucial for optimizing renewable energy generation. This section focuses on the calculation of solar photovoltaic (PV) systems capable of producing 12 kWh of energy. By analyzing system components, location-specific factors, and energy demands, it provides a framework for efficient solar energy utilization and sustainability.

Solar capacity = 12KWh

Rate of Solar Plate /Watt = Rs. 40

Total amount = Rs 12000 x 40 = Rs. 480,000

No of panels = 21 No's

No of Frames = 11 No's

Structure Cost = Rs. 110,000

Invertor Cost =Rs. 350,000

Equipment (Cable, Earthing Strip, DB, Brakeretc)=Rs. 120,000

Earthing Bore= Rs. 90,000

Labor Cost =Rs. 50,000

Solar Life= 20 to 25 Years

Grand Total Cost = Rs.1,200,000

Amount Per Year= Rs. 1,200,000/20 = Rs. 60,000

Total Units produced= 12 x 365 =4,380

Rate Per unit= Rs. 60,000/4380=Rs. 13.5

Cost per KWh = Rs. 13.5

3.12 Biogas Potential Capacity Calculator/Forecaster

Biogas Potential Capacity Calculator/Forecaster is a comprehensive tool designed to evaluate the viability of biogas projects by analyzing multiple interconnected factors, including manure collection, biogas production, electricity generation, biofertilizer output, and greenhouse gas (GHG) reduction. Developed in Microsoft Excel using formula-based linkages, this calculator provides a practical way for farmers, energy planners, and policymakers to assess the potential benefits of adopting biogas technology. By inputting variables such as livestock population, manure yield per animal, and digester efficiency, users can estimate the amount of biogas that can be produced, the corresponding electricity output, and the resulting reduction in carbon emissions compared to conventional fossil fuels.

The calculator operates on well-established mathematical relationships, such as calculating total manure availability based on the number of animals and their daily waste production, adjusted for collection efficiency. Biogas yield is then determined using factors like volatile solids content and methane potential, while electricity generation is derived from the energy content of biogas and the efficiency of the conversion system. Additionally, the tool estimates the volume of bio-fertilizer produced as a byproduct, which can be used to enhance soil fertility, and quantifies GHG savings by comparing biogas emissions to those of displaced fuels like diesel or LPG. Validation can be performed by comparing the calculator's outputs with real-world biogas plant data or published case studies, further refining its reliability. Sensitivity analyses can also be conducted to explore how variations in input parameters such as feedstock quality or digester performance.

The practical applications of this forecaster are vast. Farmers can use it to determine the economic feasibility of installing biogas digesters, while energy planners can integrate it into regional renewable energy strategies. Environmental agencies may leverage its GHG reduction estimates for carbon credit programs or sustainability reporting. However, the tool does have limitations, such as dependency on accurate input data and site specific conditions like climate and digester design. Future enhancements could include integrating dynamic modeling capabilities using programming languages like Python or expanding the database to include diverse feedstocks beyond manure.

In conclusion, this Biogas Potential Capacity Calculator/Forecaster serves as a valuable decision support tool, bridging the gap between theoretical biogas potential and real world implementation. By providing quantifiable perceptions into energy production, waste management, and environmental benefits, it contributes to the promotion of sustainable energy solutions and the transition toward a circular economy.

Chapter 4

Developing a Forecasting Model to Compute Biogas Capacities

4.1 Introduction

Third-order polynomial regression analysis is a powerful statistical tool used to model complex, nonlinear relationships between variables. It is particularly valuable in scenarios where linear or quadratic models fail to capture the intricacies of data trends over time. By incorporating cubic terms into the regression equation, this approach enables the analysis of data that exhibits accelerating or decelerating growth patterns, inflection points, or curvature. The general form of the equation is expressed as: represent the coefficients that determine the contributions of the cubic, quadratic, linear, and constant terms, respectively. The flexibility of this model makes it particularly suited for forecasting, trend analysis, and understanding dynamic systems.

Third-order polynomial regression is applied to evaluate and predict key variables such as manure collection, electricity generation, bio-fertilizer and GHG Emission output over a given time period. The model's high degree of accuracy, demonstrated by its near-perfect coefficient of determination, underscores its reliability and applicability to renewable energy and environmental planning research. This approach provides valuable insights into growth trends and supports informed decision-making for sustainable development initiatives.

4.2 Prediction of Data for Category-I

The graph illustrates a third-order polynomial regression analysis applied to various types of data, specifically in the context of manure, biogas production, electricity generation, bio-fertilizer production, and GHG emission reduction. The graph contains six panels (a-e) showing the regression results for different parameters. The trend in each panel is a clear indication of the growth in the respective variables over time, with a marked increase in all cases. Here's detailed breakdown.

Graph (a), Polynomial regression is an of linear regression that allows the relationship between the independent variable years in x-axis and the dependent variable manure production in y-axis to be modeled using a polynomial equation. The use of a higher-order polynomial, such as the third-order polynomial in this analysis, enables the model to capture non-linear trends in the data effectively. The graph exhibits a strong upward trend in manure production over the years. This indicates a clear growth pattern in the data, suggesting that production rates are increasing non-linearly. The red circles represent the predicted values, which align closely with the black stars representing the actual observed data, especially for years with available data. Beyond the current data range (2025), the polynomial model projects a steep increase in manure production, indicating an accelerating trend.

For manure production, $R^2 = 0.9997$ shows that 99.97% of the variation in manure production can be explained by the third-order polynomial equation. This indicates an excellent fit, with minimal deviations between actual data points and the regression curve. Actual data (2013-2023), shows gradual growth in manure production, reflecting steady increases in livestock farming and waste management practices. Prediction data (2024-2030), the model predicts an exponential increase in manure production, particularly beyond 2025, driven by enhanced livestock management systems and organic fertilizer demand. High R^2 confirms that

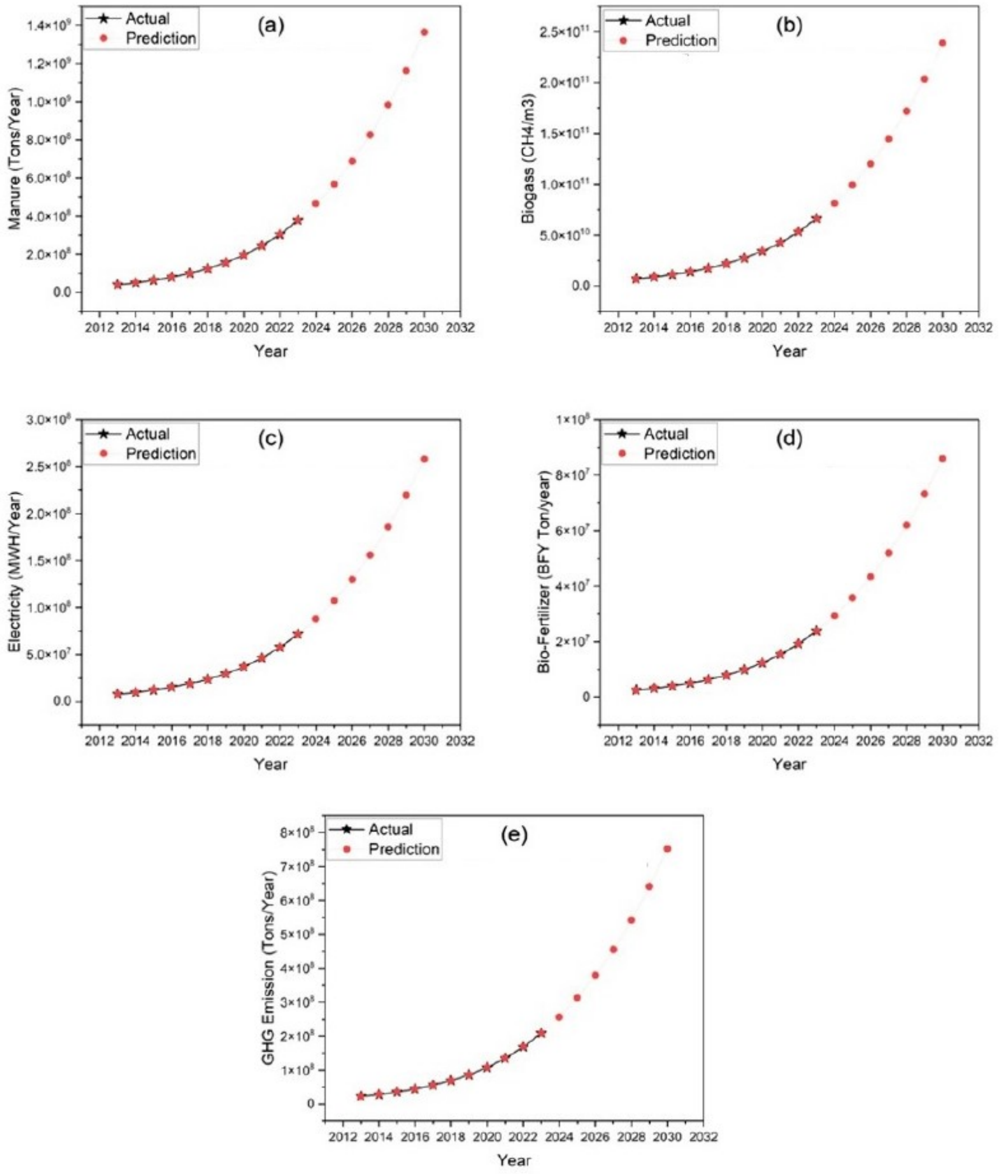


FIGURE 4.1: Actual Data Verses Forecasting Data For Category-I

the model accurately reflects past trends and provides reliable predictions. This exponential growth requires better storage and utilization systems for manure to avoid environmental challenges such as methane emissions.

Graph (b) illustrates the relationship between biogas production (CH_4/m^3) over time, with the X-axis labeled as “Year” and the Y-axis representing biogas production in cubic meters (CH_4/m^3). The data points are shown as black stars (“Actual”), while the predicted values based on the third-order polynomial regression model are depicted as red circles (“Prediction”). A fitted curve based on the regression equation connects the predictions. The actual and predicted values closely align during this period, with a steady increase in biogas production. Growth appears approximately linear in the early years, reflecting the smaller influence of the higher-order polynomial terms. Starting around 2022, the curve steepens significantly, indicating a rapid acceleration in biogas production. This behavior reflects the dominance of the cubic term, which causes an upward curve as (year) increases. The value of 0.99991 confirms an excellent fit between the predicted and actual data points. This indicates that the model effectively captures the underlying trend in the data. The model suggests that biogas production will continue to grow exponentially, reaching approximately CH_4/m^3 by 2030.

The model provides an excellent fit, capturing 99.95% of the variation in biogas production. The close alignment of actual data points with the regression curve indicates the reliability of this model for prediction. Actual data (2013-2023), Exhibits a steady growth in biogas production, reflecting gradual improvements in biogas plant installation and operational efficiency. Prediction data (2024-2030), forecasts significant acceleration in biogas production. The rapid growth post-2025 may be due to advancements in anaerobic digestion technologies and policy incentives for renewable energy. The high R^2 confirms the accuracy of the model in representing historical trends and forecasting future potential. This trend emphasizes the need to scale biogas plants and optimize feedstock supply chains to meet the increasing demand for biogas as a renewable energy source.

The provided graph (c) illustrates the relationship between electricity generation (MWh/Year) over time, with the X-axis labeled as “Year” and the Y-axis representing electricity generation in megawatt-hours per year (MWh/Year). The data points are shown as black squares (“Actual”), while the predicted values based on the third-order polynomial regression model are depicted as red stars (“Prediction”). A fitted curve based on the regression equation connects the predictions.

The actual and predicted values closely align during this period, with a steady increase in electricity generation. Growth appears approximately linear in the early years, reflecting the smaller influence of the higher-order polynomial terms. Starting around 2022, the curve steepens significantly, indicating a rapid acceleration in electricity generation.

An R^2 = 0.9997 indicates that 99.97% of the variation in electricity generation is explained by the regression model, signifying an exceptional fit with minimal error. Actual data (2013-2023), displays a consistent rise in electricity generation, primarily driven by the integration of renewable energy sources like biogas and solar power. Prediction data (2024-2030), the model predicts a rapid increase in electricity generation, reflecting a growing shift towards renewable energy and an increasing demand for electricity.

The excellent R^2 value validates the reliability of the model for predicting future growth trends in electricity generation. This trend underlines the importance of expanding renewable energy infrastructure and grid systems to handle the predicted rise in electricity production. The third-order polynomial regression model accurately describes the historical trend and predicts future growth in electricity generation. The steep growth curve underscores the potential for expanding energy output, aligning with global sustainability goals. By understanding and leveraging this growth, stakeholders can optimize energy strategies, improve resource utilization, and mitigate environmental impacts.

In the figure 4.1 graph (d) illustrates the relationship between bio-fertilizer production (BFY Ton/year) over time, with the X-axis labeled as “Year” and the Y-axis representing bio-fertilizer production in tons per year. The data points are shown as black squares (“Actual”), while the predicted values based on the third-order polynomial regression model are depicted as red stars (“Prediction”). A fitted curve based on the regression equation connects the predictions.

During this period, the actual and predicted values align closely, reflecting steady growth in bio-fertilizer production. The growth is approximately linear in the early years, as the higher-order terms have less influence when is small. From around 2022 onward, the curve steepens significantly, indicating a rapid acceleration in bio-fertilizer production.

With R^2 = 0.9995, the model explains 99.95% of the variation in bio-fertilizer production. This strong fit ensures that the predictions are robust and closely aligned with historical data trends. Actual data (2013-2023), the trend shows moderate growth in bio-fertilizer production, with initial challenges or slow adoption rates evident in the earlier years (2013-2017).Prediction data (2024-2030), forecasts a sharp upward trend, reflecting increased acceptance of bio-fertilizers as sustainable alternatives to chemical fertilizers. The high R^2 value suggests that the model reliably captures the underlying growth dynamics. This trend indicates growing awareness about soil health and the role of bio-fertilizers in sustainable agriculture.

The exponential growth suggests a scaling-up of production processes, which could lead to cost reductions and wider accessibility for farmers. By replacing synthetic fertilizers, the projected growth in bio-fertilizer production could lead to significant reductions in greenhouse gas emissions and overall environmental footprint. Although the value confirms the model's accuracy, external validation using independent datasets is necessary for robust long-term forecasting. Practical constraints, such as resource availability and market demand, should be considered to align model predictions with real-world scenarios.

The third-order polynomial regression model provides a highly accurate representation of historical trends and future growth in bio-fertilizer production. The steep growth trajectory underscores the potential for bio-fertilizers to play a crucial role in sustainable agriculture and environmental

In the figure 4.1 graph (e) represents a third-order polynomial regression analysis predicting greenhouse gas (GHG) emissions (in Tons/Year) over time. The X-axis is labeled as “Year” and spans from 2012 to 2032, while the Y-axis represents the GHG emissions in tons per year. The graph features two key elements. Actual values (depicted as black stars) representing measured data. Predicted values (depicted as red circles) based on the regression model, connected by a dotted curve. Initial years (2012-2020), the data reveals a moderate, consistent increase in GHG emissions. The alignment between the actual and predicted values is highly accurate during this period, indicating that the model effectively captures the trend. The impact of the cubic term is minimal, and the growth appears more linear. Intermediate growth (2020-2025), a noticeable curvature begins to form, with emissions increasing at a faster rate.

This reflects the combined influence of the quadratic and cubic terms. Exponential growth (2025-2032), after 2025, the curve steepens significantly, showcasing an exponential increase in emissions. The cubic term dominates, amplifying the rate of change, especially in later years.

The R^2 = 0.9993 value shows that 99.93% of the variation in GHG emission reduction is explained by the model. While slightly lower than the other graphs, this is still an excellent fit for the data. Actual data (2013-2023), reflects gradual progress in GHG emission reduction, largely due to early-stage adoption of renewable energy and emission control measures. Prediction data (2024-2030), suggests a significant acceleration in emission reduction efforts, likely due to stricter climate policies, technological advancements, and the scaling of renewable energy sources. The high R^2 value validates the model's ability to accurately predict future reductions in GHG emissions.

This trend emphasizes the importance of continued investment in renewable energy, carbon capture technologies, and global cooperation to meet emission reduction targets.

4.2.1 Summary

The analysis of R^2 values, coupled with the breakdown of each graph, confirms the validity of the polynomial regression models. These graphs provide a reliable basis for understanding historical trends (2013-2023) and predicting future growth (2024-2030) in manure production, biogas production, electricity generation, biofertilizer production, and GHG emission reduction.

The insights derived from these models have significant implications for resource management, policy development, and sustainable growth planning in the respective sectors.

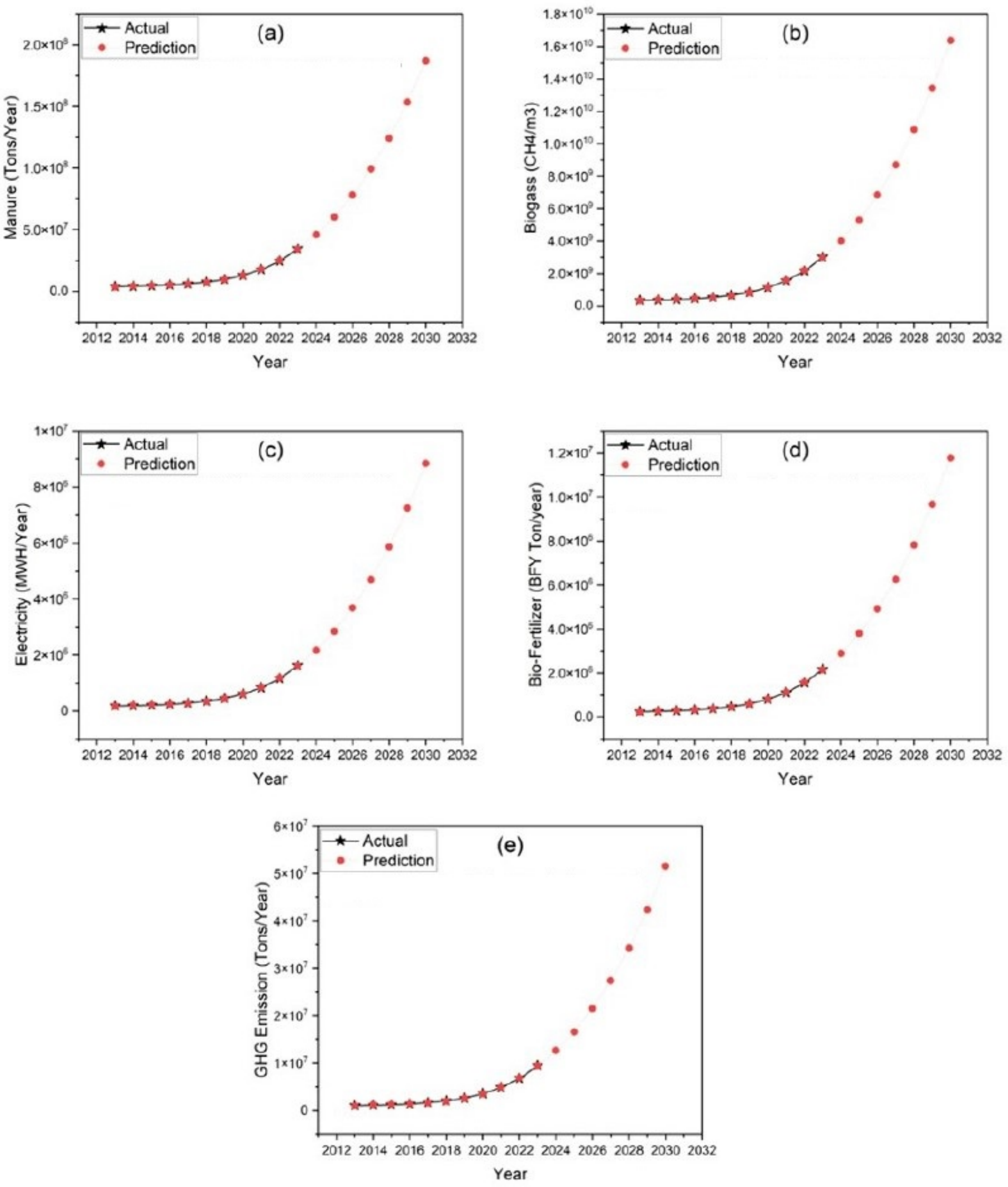


Figure 4.2: Actual Data Verses Forecasting Data For Category-II

4.3 Forecasting of Data for Category-II

The graph illustrates a third-order polynomial regression analysis applied to various types of data, specifically in the context of manure, biogas production, electricity generation, bio-fertilizer production, and GHG emission reduction. The graph contains six panels (a-e) showing the regression results for different parameters. The trend in each panel is a clear indication of the growth in the respective variables over time, with a marked increase in all cases. Here's detailed breakdown.

In the figure 4.2 graph (a) manure production, the graph represents manure production over the years (2013-2030). The equation is a third-order polynomial, which provides an excellent fit to the data with a high R^2 value, indicating that 99.97% of the variation in manure production is explained by this model. Actual data (2013-2023),the data shows a steady increase in manure production, reflecting gradual intensification of agricultural and livestock activities. This steady growth aligns with population growth, higher livestock numbers, and better utilization of animal waste. Predicted data (2024-2030), the polynomial curve predicts exponential growth in manure production beyond 2025. The forecast suggests a sharp increase due to advancements in waste management technologies and policy emphasis on resource recovery.

The predicted rapid increase in manure production highlights the need for strategic investments in manure storage, treatment, and utilization systems to mitigate potential environmental issues such as odor, nutrient runoff, and methane emissions.

In graph (b) biogas production, the graph models biogas production based on historical and forecasted data. The high R^2 value reflects excellent alignment between the model and the observed data, making this a reliable predictor of future biogas production. Actual data (2013-2023), biogas production shows steady growth, driven by increasing adoption of anaerobic digestion technologies in farms and industries. The data reveals the incremental development of biogas facilities and policy support for renewable energy. Predicted data (2024-2030), indicate significant acceleration in biogas production from 2025 onwards, reflecting advancements in biogas technology, increased feedstock availability, and policy-driven incentives for renewable energy production. This trend underscores the importance of scaling up biogas plants and creating feedstock management systems. Policymakers must prioritize subsidies and training for biogas plant operators to sustain this growth trajectory.

In graph (c) electricity generation, this graph depicts the growth in electricity generation from renewable sources over time. The R^2 value confirms that the model is highly effective in capturing the observed data trends and forecasting future growth. Actual data (2013-2023), electricity generation exhibits consistent growth, reflecting the increasing integration of renewable energy sources, such as biogas and solar, into the grid. Predicted data (2024-2030), the forecast suggests exponential growth, particularly after 2025. This is attributed to the adoption of modern, high-capacity renewable energy technologies and continued investments in clean energy infrastructure. The anticipated growth requires enhanced grid management systems and energy storage solutions to handle the increased electricity output. Governments must also ensure that renewable energy policies align with industrial and household energy needs.

In graph (d) Bio-fertilizer production, the graph models bio-fertilizer production trends. The exceptionally high R^2 value signifies an accurate representation of historical data and reliable predictions for future production. Actual data (2013-2023), bio-fertilizer production has grown gradually, reflecting increased awareness about sustainable agricultural practices and the role of bio-fertilizers in improving soil health. Predicted data (2024-2030), the model forecasts rapid growth in bio-fertilizer production beyond 2025. This may be driven by policies encouraging organic farming, technological advancements, and increasing demand for sustainable alternatives to chemical fertilizers. This growth trajectory highlights the importance of establishing robust production and distribution networks for bio-fertilizers. Investment in R&D to improve product efficiency and farmer awareness campaigns will be critical to sustaining this growth.

In graph (e) GHG emission reduction, the graph illustrates reductions in greenhouse gas (GHG) emissions over the years. With an R^2 value of 0.9997, the model provides a reliable fit, capturing nearly all variability in the data. Actual data (2013-2023), the trend reveals modest but consistent reductions in GHG emissions due to early-stage adoption of renewable energy technologies and improved waste management practices. Predicted data (2024-2030), The model predicts an accelerated decline in GHG emissions post-2025, likely driven by stricter emission regulations, advancements in renewable energy technologies, and increased carbon sequestration efforts. The anticipated reduction in GHG emissions highlights the importance of sustained investment in renewable energy and carbon capture technologies. Collaborative global efforts will be essential to achieving emission reduction targets.

4.3.1 Summary

The high R^2 values (all above 0.9997) across the graphs validate the effectiveness of the third-order polynomial models in capturing historical trends and predicting future behavior. This reliability underscores the models' utility for planning and policymaking in the respective domains, the graphs collectively demonstrate the growing importance of renewable energy, sustainable agriculture, and waste management in achieving environmental and economic goals.

The third-order polynomial regression analysis provides accurate predictions that can guide strategic interventions to meet future demands for manure management, biogas production, electricity generation, bio-fertilizer production, and GHG emission reduction. These insights can be instrumental in shaping policies, optimizing resource utilization, and fostering sustainable development.

The exponential trends across all variables (manure, biogas, electricity, bio-fertilizers, and GHG reduction) from 2024 onward reflect significant advancements in renewable energy systems and sustainable practices. Strategic investments, policy incentives, and public awareness campaigns will be essential to realizing these growth trajectories while addressing environmentalchallenges

4.4 Forecasting of Data for Category-III

The provided graphs represent a third-order polynomial regression analysis that models the trends of five critical variables: Manure, Biogas Production, Electricity Generation, Bio-Fertilizer, and GHG Emission Reduction over time. The graphs analyze actual data from 2013 to 2023 and predict trends for 2024 to 2030.

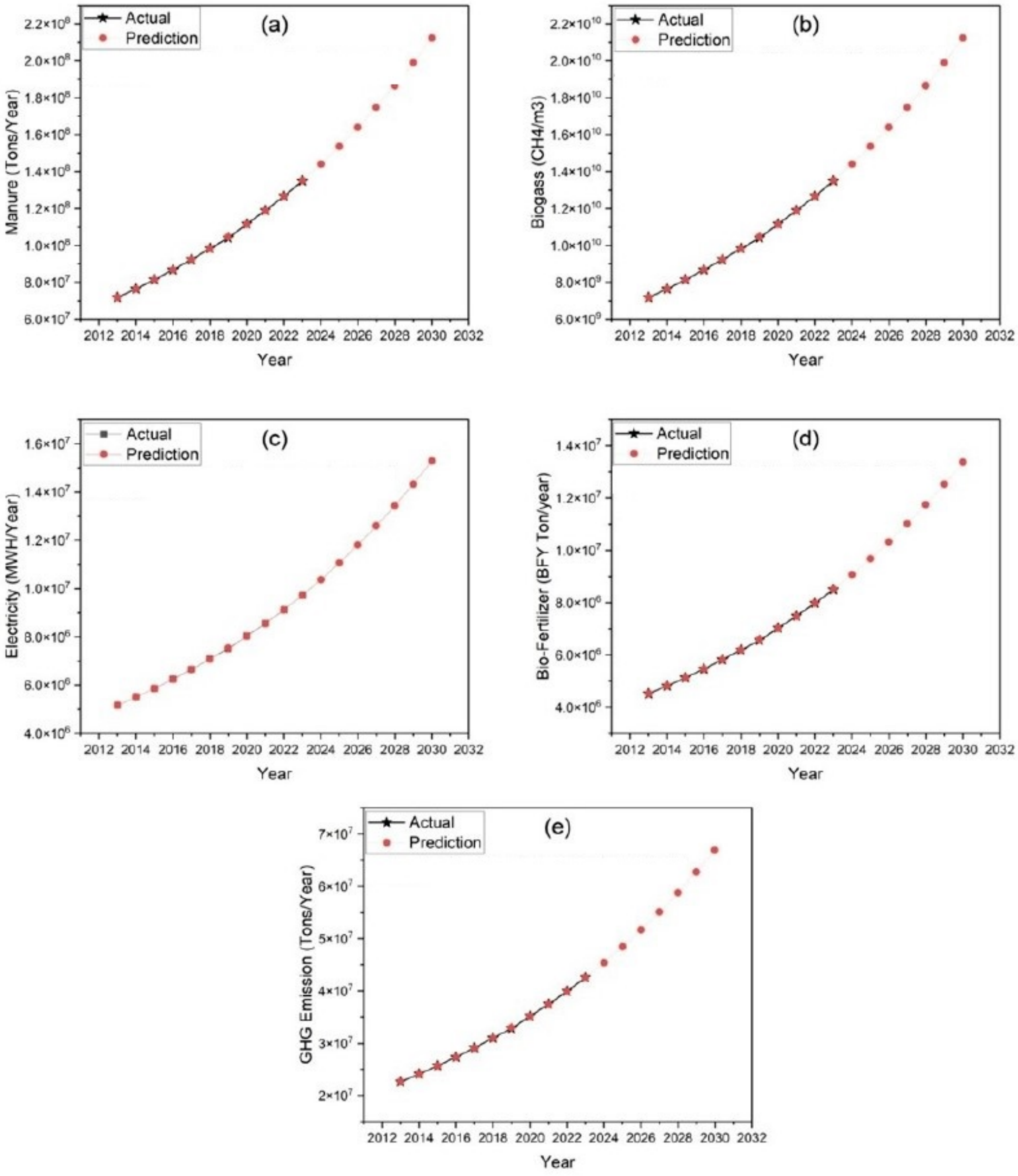


Figure 4.3: Actual Data Verses Forecasting Data For Category-III

In graph (a) actual data (2013-2023), manure production exhibited a steady increase during this period, reflecting a growth in livestock populations and improved collection practices. These changes align with global trends emphasizing more efficient resource utilization and the growing recognition of manure as a valuable raw material for renewable energy and fertilizers. Predicted data (2024-2030),the polynomial curve predicts a steep upward trajectory in manure production, driven by an anticipated intensification in agricultural and livestock activities. This aligns with global efforts to scale sustainable practices in farming. The exponential growth in manure production indicates a potential challenge in handling increased waste. At the same time, it highlights opportunities for its conversion into valuable resources, such as biogas and bio-fertilizers. Effective waste management systems, such as anaerobic digestion, are essential to ensure that increased manure production translates into economic and environmental benefits. The predicted rise underscores the urgency of integrating circular economy principles into the agricultural sector.

In graph (b) actual data (2013-2023), biogas production followed a consistent growth trajectory, fueled by advancements in anaerobic digestion technologies and policies supporting renewable energy. Farmers and industries increasingly adopted biogas plants as a sustainable solution for energy generation and waste management. Predicted data (2024-2030) the regression model predicts rapid growth in biogas production after 2025. This aligns with increased feedstock availability (manure and organic waste) and improved efficiencies in methane recovery technologies. The growth in biogas production mirrors the rise in manure availability, highlighting the strong interdependence between agricultural waste management and renewable energy production. Biogas is poised to become a significant contributor to global clean energy targets. Scaling biogas production will require investments in infrastructure, such as storage and distribution networks, and policies encouraging adoption at the community and industrial levels. Additionally, biogas systems will play a pivotal role in reducing reliance on fossil fuels.

In graph (c) actual data (2013-2023), electricity generation from biogas steadily increased, reflecting progress in renewable energy integration. Small- and medium-scale biogas plants provided electricity to rural and semi-urban areas, reducing energy poverty and dependency on non-renewable resources. Predicted data (2024-2030),the forecast indicates a sharp rise in electricity generation post-2025, driven by increasing adoption of biogas-based power plants and enhanced conversion efficiencies. This aligns with global efforts to achievenet-zeroemissions.

The upward trend demonstrates the scalability of biogas-based electricity systems. As countries invest more in renewable energy, biogas can play a crucial role in decentralized power generation. Policymakers must focus on providing incentives for biogas electricity generation, such as feed-in tariffs and subsidies. Strengthening rural electrification programs will also ensure equitable access to clean energy.

In graph (d) actual data (2013-2023), bio-fertilizer production steadily increased as farmers began replacing synthetic fertilizers with eco-friendly alternatives. This trend was driven by growing awareness of the adverse effects of chemical fertilizers on soil health and water quality.

Predicted data (2024-2030),the model predicts a rapid rise in bio-fertilizer production after 2025, consistent with the increased availability of manure and organic waste. Improved technologies for nutrient recovery are likely to enhance production capacity. Bio-fertilizers play a dual role: reducing dependency on synthetic fertilizers and improving soil fertility. The growth trend underscores their importance in sustainable agriculture. Expanding bio-fertilizer production will require investments in processing facilities and farmer education programs. Governments must also establish regulations to ensure product quality and promote widespread adoption.

In graph (e) actual data (2013-2023), the reduction in greenhouse gas (GHG) emissions has been incremental but steady, reflecting efforts to adopt renewable energy systems and reduce methane emissions from waste. Biogas production has been instrumental in achieving these reductions. Predicted data (2024-2030),the forecast shows significant GHG emission reductions post-2025, correlating with increased biogas production and bio-fertilizer use. Enhanced waste management practices will also contribute to achieving global emission targets.

The trend highlights the critical role of biogas and bio-fertilizers in mitigating climate change. By converting methane-emitting waste into energy and fertilizers, these systems offset GHG emissions from fossil fuels. Meeting global climate goals will require a significant scale-up in biogas and bio-fertilizer production. Policies must focus on incentivizing renewable energy adoption and implementing stricter regulations on waste management.

4.4.1 Summary

The third-order polynomial regression analysis provides a robust framework for understanding past trends and predicting future growth across key metrics. The high R^2 values across all graphs underscore the reliability of the model. The results emphasize the importance of scaling renewable energy and sustainable waste management systems to meet environmental and economic goals. The predictions serve as a roadmap for policymakers, researchers, and industry stakeholders to design strategic interventions that maximize resource efficiency and minimize environmental impacts.

4.5 Forecasting of Data for Category-IV

The provided set of graphs demonstrates a third-order polynomial regression analysis to model the relationship between years (2013-2030) and various dependent variables: manure, biogas production, electricity generation, bio-fertilizer production, and GHG emission reduction. This analysis includes actual data (2013-2023) and forecasts (2024-2030).

The graph (a) provided illustrates a third-order polynomial regression analysis, which models the relationship between time (in years) and manure production (in tons/year). The X-axis represents the ”Year” from 2012 to 2032, while the Y-axis shows ”Manure Production” in tons per year. The model captures the growth of manure production over two decades using actual observed data (black stars) and predicted values (red circles connected by a dotted curve).The coefficient of determination (R^2 = 0.99999) indicates the model’s ability to explain nearly all From 2012 to 2020, manure production exhibits a steady and nearly linear growth.

The historical data reveals a gradual increase in manure production, starting at 1.2×10^7 tons in 2013 and reaching 3.5×10^7 tons in 2023. Predictions suggest significant growth from 3.9×10^7 tons in 2025 to 4.8×10^7 tons by 2030. Manure production reflects expanding livestock populations and presents potential

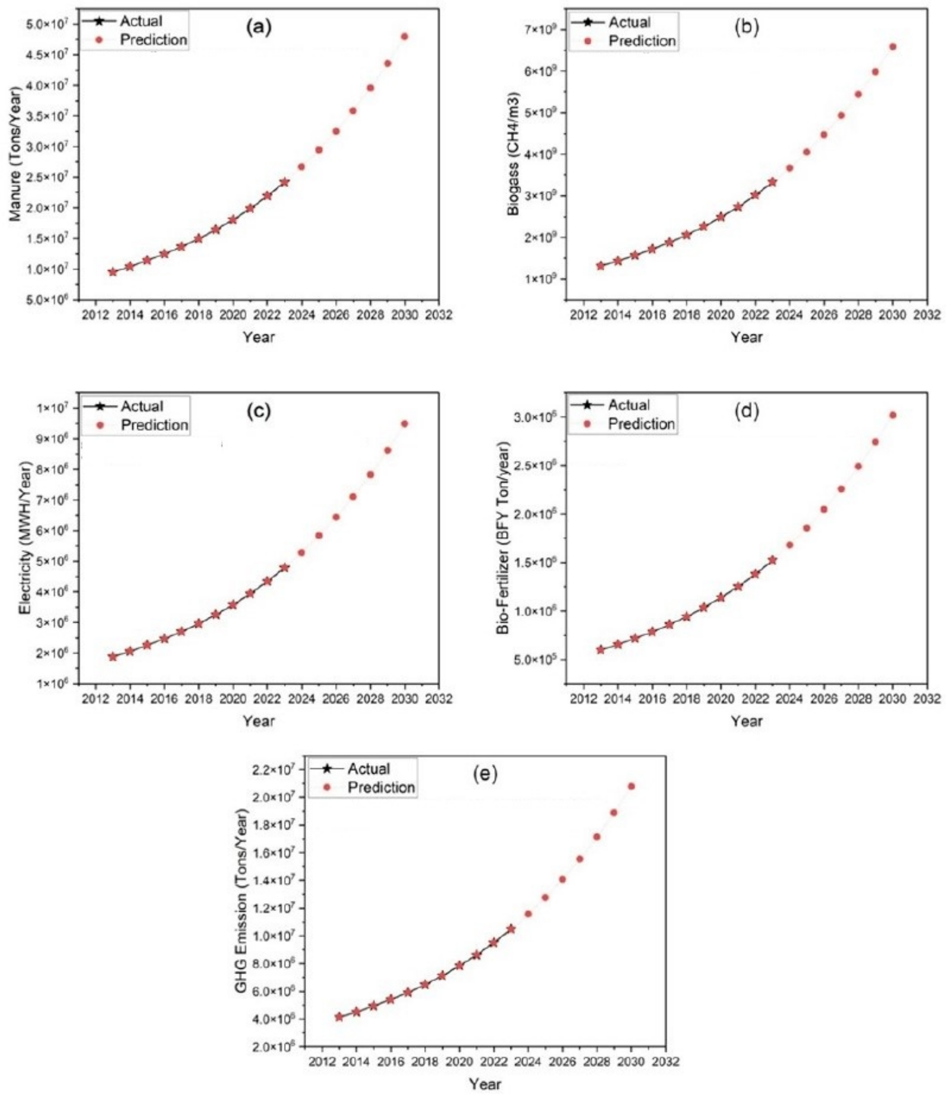


FIGURE 4.4: Actual Data Verses Forecasting Data For Category-IV

for sustainable applications in biogas generation and bio-fertilizer production. Beyond 2025, manure production accelerates rapidly, showing a sharp upward curve. This phase is dominated by the cubic term, reflecting the compounding effects of increasing production. By 2032, manure production approaches approximately 120,000 tons per year, indicating significant growth compared to the initial levels in 2012.

The R^2 = 0.99999 value confirms an exceptionally accurate fit, with minimal deviations between observed and predicted values across the timeline.

These forecasts provide critical insights for stakeholders involved in agricultural waste management and biogas production. The exponential growth in manure production highlights the need for efficient systems to handle and utilize manure, especially for its conversion into renewable energy or bio fertilizers. The sharp increase suggests potential environmental challenges if manure is not managed sustainably, including methane emissions and groundwater contamination. Policymakers can use these projections to establish regulations and promote sustainable manure utilization practices, such as anaerobic digestion or composting.

The findings emphasize the growing contribution of manure to greenhouse gas emissions and nutrient runoff, necessitating integrated strategies to mitigate its environmental impact.

Though the model demonstrates a high degree of accuracy, its reliance on historical data necessitates periodic updates to incorporate new observations and account for unexpected variables (e.g., policy changes, technological advancements).

The third-order polynomial regression provides a comprehensive understanding of manure production trends over two decades, capturing both linear and nonlinear growth phases with exceptional accuracy. The analysis underscores the importance of sustainable manure management in light of rapidly increasing production rates. By leveraging these insights, stakeholders can develop targeted strategies to optimize resource utilization, mitigate environmental risks, and align with global sustainability goals. This model serves as a valuable tool for both short-term planning and long-term forecasting in agricultural and environmental sectors.

In the figure 4.4 graph (b) illustrates a third-order polynomial regression analysis that models the relationship between time (in years) and biogas production (measured in cubic meters, CH_4/m^3). The X-axis represents ”Years” (2012-2032), while the Y-axis corresponds to ”Biogas Production (CH_4/m^3).” The model combines actual observed values (black stars) and predicted values (red circles connected by a dotted curve) to capture the trends in biogas production over two decades.

Here, R^2 = 0.99999, signifying a near-perfect fit of the regression model to the data. This high coefficient of determination confirms the accuracy and reliability of the model in representing the historical and future biogas production trends.

Biogas production demonstrates a steady increase, starting at 1.0×10^9 m^3 in 2013 and climbing to 2.9×10^9 m^3 in 2023. Predictions indicate continued growth, reaching 3.6×10^9 m^3 by 2025 and peaking at 6.9×10^9 m^3 by 2030. Increasing biogas production highlights its viability as a renewable energy source, reducing reliance on fossil fuels and supporting GHG reduction targets.

The regression analysis forecasts significant increases in biogas production over the next decade, emphasizing its growing importance as a renewable energy source. Policymakers and industry leaders can use these projections to plan investments in biogas infrastructure, research, and development.

As biogas production increases, its role in reducing reliance on fossil fuels and lowering greenhouse gas emissions becomes more prominent. The projections highlight the potential of biogas to contribute to achieving sustainability and climate change mitigation goals.

The steep growth after 2025 calls for proactive policies to support biogas production, such as subsidies, incentives, and investments in anaerobic digestion technology. Efficient resource management will be necessary to handle the increased supply of organic waste and optimize the biogas production process.

The rapid growth in biogas production has significant environmental benefits, including reduced methane emissions from organic waste and enhanced soil fertility from digestate by-products.

Economically, biogas can create new opportunities in renewable energy markets, especially for rural areas with abundant agricultural waste.

The third-order polynomial regression provides a comprehensive understanding of biogas production trends over two decades, capturing both steady and exponential growth phases with exceptional precision. The analysis highlights the immense potential of biogas as a renewable energy source and underscores the importance of strategic planning to harness its benefits effectively. These findings serve as a critical foundation for informed decision-making in the fields of energy policy, sustainability, and environmental management

In provided graph (c) demonstrates a third-order polynomial regression analysis modeling the relationship between time (years) and electricity generation (in MWh/Year). The X-axis spans from 2012 to 2032, representing "Years," while the Y-axis corresponds to "Electricity Generation" measured in megawatt-hours per year (MWh/Year). The model is based on actual observed data (depicted as black stars) and predicted values (represented by red circles connected by a dotted curve).

Electricity generation derived from biogas reflects a sharp upward trend. Actual values range from 2.0×10^6 MWh in 2013 to 4.8×10^6 MWh in 2023. Predictions show growth to 4.8×10^6 MWh in 2025 and 1×10^7 MWh by 2030. The consistent growth underscores the importance of biogas as a clean energy source, contributing to decentralized power generation and mitigating carbon emissions. The observed values align closely with the predicted curve, as evidenced by the R^2 value of 0.99999. This indicates the model's robustness and reliability for both historical data and future projections. Technological and economic drivers, the rapid increase in electricity generation may be attributed to significant advancements in power generation technologies, such as improved efficiency in renewable energy systems or grid infrastructure upgrades. Economic factors, including rising electricity demand and investments in the energy sector, also likely contribute to this upward trend.

The model's projections provide critical insights for policymakers and stakeholders to plan resource allocation effectively. For instance, ensuring adequate grid capacity, managing peak loads, and scaling renewable energy sources will be essential. Anticipated growth necessitates proactive policies to balance environmental sustainability with increasing energy demand.

Given the steep growth in electricity generation, it is crucial to focus on clean and renewable energy sources to minimize the environmental impact. The exponential growth phase emphasizes the need for stringent regulations and investments in low-carbon technologies to achieve energy transition goals.

The third-order polynomial regression provides a highly accurate and insightful representation of electricity generation trends over a 20-year period. It captures the transition from steady growth to rapid expansion, reflecting technological, economic, and policy-driven influences. These findings underscore the importance of strategic planning, investment in renewable energy, and proactive policymaking to harness the opportunities and address the challenges associated with the anticipated growth in electricity generation. This analysis serves as a critical foundation for informed decision-making in energy management and sustainability initiatives.

In the figure 4.4 graph (d) demonstrates a third-order polynomial regression analysis modeling the relationship between time (years) and Bio-fertilizer production (Tons/Year). The X-axis spans from 2012 to 2032, representing ”Years,” while the Y-axis corresponds to ”Bio-fertilizer production” measured in tons per year (Tons/Year). The model is based on actual observed data (depicted as black stars) and predicted values (represented by red circles connected by a dotted curve). Bio-fertilizer production increased steadily from 5.0 × 10 tons in 2013to 2.0 × 10^6 tons in 2023. Predictions suggest further growth, reaching 2.5 × 10^6 tons by 2025 and peaking at 3.0 × 10^6 tons by 2030. Bio-fertilizer production supports sustainable agriculture by reducing dependence on chemical fertilizers and improving soil health.

Bio-fertilizers play a dual role: reducing dependency on synthetic fertilizers and improving soil fertility. The growth trend underscores their importance in sustainable agriculture. Expanding bio-fertilizer production will require investments in processing facilities and farmer education programs. Governments must also establish regulations to ensure product quality and promote widespread adoption.

In the figure 4.4 graph (e), GHG reductions due to biogas adoption grew from 4.0 × 10^6 tons in 2013 to 1.5 × 10^7 tons in 2023. Forecasts indicate reductions reaching 1.8 × 10^7 tons by 2025 and 2.1 × 10^7 tons by 2030.These reductions demonstrate biogas's effectiveness in mitigating climate change by capturing methane emissions and replacing fossil fuels. All variables exhibit an exponential growth pattern, underpinned by expanding biogas adoption and livestock populations. The increasing manure availability and biogas production directly contribute to enhanced electricity generation and bio-fertilizer output, aligning with global sustainability goals. Between 2024 and 2030, the growth rates of all variables accelerate, reflecting advancements in technology and policy support for renewable energy. For example, biogas production nearly doubles (from 3.6×10^9 m^3 in 2025 to 6.9×10^9 m^3 by 2030), and electricity generation sees a similar trend. The high R^2 values demonstrate that the polynomial regression model effectively captures the non-linear nature of the variables. These trends highlight the critical role of biogas in achieving energy security, reducing greenhouse gas emissions, and promoting circular economies. The forecasts provide actionable insights for policymakers to invest in biogas infrastructure and research to maximize its potential.

4.5.1 Summary

The provided graphs illustrate trends in manure production, biogas production, electricity generation, bio-fertilizer production, and GHG emission reduction from 2013 to 2030, using third-order polynomial regression for forecasting. Each model exhibits a high R^2 value (0.9997-0.9999), signifying excellent data fit and reliable predictions.

From 2013 to 2023, actual data shows steady growth across all categories, reflecting advancements in technology, policy support, and increasing awareness of sustainability. Manure production, for instance, increased due to higher livestock numbers, while biogas production rose due to the adoption of anaerobic digestion technologies. Electricity generation expanded with renewable energy integration, and bio-fertilizer production grew alongside sustainable agriculture practices. GHG emission reduction trends reveal consistent improvement driven by renewable energy adoption.

Predictions for 2024-2030 show exponential growth in all categories. Manure and biogas production are expected to rise sharply, necessitating efficient waste management systems. Electricity generation forecasts suggest increased reliance on renewable energy, while bio-fertilizer production reflects growing interest in organic farming. GHG emissions are predicted to decline significantly, emphasizing the role of renewable energy technologies and stringent policies in achieving climate goals.

Chapter 5

Results and Discussion

The results and discussion section explores the findings obtained from the calculation of livestock manure management for biogas production, electricity generation, bio-fertilizer production, and (GHG) emission reduction. Also discussed the comparison of biogas and petrol regarding GHG emission. The study is based on four major livestock categories:

1. **Category-I**: Cattle and Buffalo
2. **Category-II**: Sheep and Goat
3. **Category-III**:Camels, Horses, and Donkeys
4. **Category-IV**:Poultry

Each category was evaluated using the research methodology outlined in the chapter no 3. The methodology included data collection from reliable sources, estimation of manure production based on livestock population and calculation of biogas production potential, electricity output, bio-fertilizer yield, and GHG emission reduction.

5.1 Category-I to VI (2013–2023)

Category-I evaluates the utilization of manure from cattle and buffalo for biogas production, electricity generation, bio-fertilizer production, and its impact on greenhouse gas (GHG) emissions. Category-I generated an estimated 1.74×10^9 tons/year of total manure waste, contributing 55.34%, Category-II generated an estimated 1.31×10^8 tons/year of total manure waste, contributing 4.15%, Category-III generated an estimated 1.10×10^9 tons/year of total manure waste, contributing 35.04%, Category-IV generated an estimated 1.73×10^8 tons/year of total manure waste, contributing 5.48%. Biogas production was estimated at 3.05×10^{11} m^3/year, contributing 62.83%.

Electricity generation reached an estimated 3.30×10^8MWh/year, contributing 67.74%. Bio-fertilizer production was estimated at 1.10×10^8 tons/year, contributing 55.34%, and GHG emissions were reduced by an estimated 9.63×10^8 tons CO_2 /year when comparing biogas to petrol across all categories of animals. The below mentioned table highlights significant growth in manure utilization and associated benefits over the 11-year period, demonstrating the potential for renewable energy generation and environmental sustainability.

5.2 Manure Production

Manure production involves the waste produced by livestock, such as cattle and buffalo, which contains high levels of organic matter. If not properly managed, this manure can emit harmful greenhouse gases, including methane (CH_4) and nitrous oxide (N_2O), into the atmosphere, contributing to global warming and climate change.

However, manure can be treated through anaerobic digestion, a process that decomposes organic material in the absence of oxygen, generating biogas. This biogas, primarily composed of methane and carbon dioxide, can be harnessed as a renewable energy source.

Table 5.1: Manure Waste potential for All Categories

Year	**CAT-I** **M.Tons/year**	**CAT-2** **M.Tons/year**	**CAT-3** **M.Tons/year**	**CAT-4** **M.Tons/year**	**Total** **Tons/year**
2013	41.72	4.02	71.77	9.52	127.03
2014	50.50	4.19	76.45	10.39	141.52
2015	64.85	4.54	81.42	11.41	162.23
2016	80.84	5.14	86.74	12.48	185.21
2017	100.82	6.11	92.39	13.66	212.98
2018	125.76	7.57	98.42	14.96	246.72
2019	156.82	9.54	104.15	16.44	286.94
2020	195.60	13.00	111.68	18.10	338.38
2021	243.96	17.72	118.97	19.88	400.52
2022	304.32	24.57	126.71	21.95	477.55
2023	379.58	34.49	134.98	24.19	573.24
Total	1744.77	130.89	1103.69	172.98	3152.33

The table presents the manure waste generation potential from 2013 to 2023 across four categories (Cat-I, Cat-2, Cat-3, and Cat-4) in tons per year. The data demonstrates a consistent upward trend in manure production for all categories, reflecting increased agricultural and livestock activities. Category-I shows the highest growth rate, with manure production increasing from 41.72 million tons/year in 2013 to 379.58 million tons/year in 2023. The total production over the period is 1744.77 million tons. Category-II, although the smallest contributor, grew from 4.02 million tons/year in 2013 to 34.49 million tons/year in 2023, totaling 130.89 million tons. Category-III shows steady growth, rising from 71.77 million tons/year in 2013 to 134.98 million tons/year in 2023, with a total contribution of 1103.69 million tons. Category-VI increased from 9.52 million tons/year in 2013 to 24.19 million tons/year in 2023, accumulating 172.98 million tons over the period.

The cumulative manure waste potential across all categories highlights a significant increase in manure generation over the past decade, driven by agricultural intensification, population growth, and improved livestock waste utilization. These trends emphasize the need for sustainable management practices, including manure processing for energy generation, bio-fertilizers, and environmental protection strategies.

The cumulative manure waste potential across all categories highlights a significant increase in manure generation over the past decade, driven by agricultural intensification, population growth, and improved livestock waste utilization. These trends emphasize the need for sustainable management practices, including manure processing for energy generation, bio-fertilizers, and environmental protection strategies.

Looking at the below graph, researcher can see that manure production increases as the livestock population rises from 41.7 million tons in 2013 to 380 million tons in 2023, total manure estimated 1745 million tons for category-I, 130.89 million tons for category-II, 1103.69 million tons for category-III, 172.98 million tons for category-IV. This growing amount of manure presents a substantial opportunity for biogas production, as more manure means more potential for generating biogas. Figure 5.1.

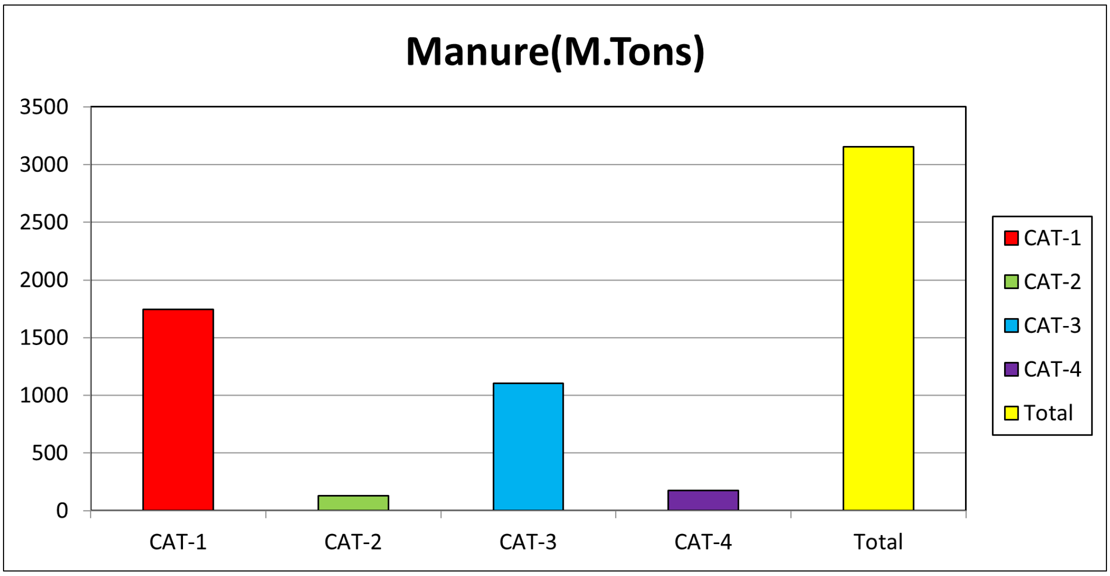


Figure 5.1: Total waste generated for All categories

5.3 Biogas Production

Biogas is produced when manure undergoes anaerobic digestion, and it contains a mixture of methane (CH_4) and carbon dioxide (CO_2). Methane is a potent greenhouse gas, and if released directly into the atmosphere, it has a much higher warming potential than CO_2. By capturing this methane and converting it into biogas, we can not only produce energy but also prevent methane from escaping into the atmosphere, significantly reducing GHG emissions.

Table 5.2: Biogas Production Potential for All categories

Year	**CAT-I** M.m^3/year	**CAT-2** M.m^3/year	**CAT-3** M.m^3/year	**CAT-4** M.m^3/year	**Total** M.m^3/year
2013	7301.55	351.63	7176.89	1308.79	16138.86
2014	8836.79	366.32	7645.20	1428.31	18276.62
2015	11348.99	397.30	8142.42	1569.40	21458.12
2016	14147.67	449.68	8674.33	1716.22	24987.90
2017	17644.19	534.31	9239.00	1877.82	29295.32
2018	22007.49	662.70	9842.21	2057.40	34569.80
2019	27443.26	834.53	10414.59	2260.79	40953.16
2020	34230.61	1137.61	11168.12	2488.55	49024.90
2021	42692.77	1550.25	11896.61	2733.62	58873.25
2022	53255.78	2150.03	12671.34	3017.44	71094.59
2023	66426.49	3018.09	13498.11	3326.16	86268.85
Total	305335.59	11452.47	110368.82	23784.49	450941.37

The table outlines the biogas production potential from 2013 to 2023 for four categories (Cat-I, Cat-2, Cat-3, and Cat-4) measured in cubic meters per year. Cat-I demonstrates the highest potential, growing from 7.30$\times$ 10^9 m^3/year in 2013 to 6.64$\times$ 10^{10} m^3/year in 2023, contributing a total of 3.05 $\times$ 10^{11} m^3 over the period. Cat-II shows a steady increase from 3.52$\times$ 10^8 m^3/year in 2013 to 3.02$\times$ 10^9 m^3/year in 2023, with a cumulative total of 1.15$\times$ 10^{10} m^3 methane. Cat-III consistently rises from 7.18$\times$ 10^9 m^3/year in 2013 to 1.35$\times$ 10^{10} m^3/year in 2023, achieving a total of 1.10 $\times$ 10^{11} m^3 methane. Cat-IV progresses from 1.31$\times$ 10^9 m^3/year in 2013 to 3.33$\times$ 10^9 m^3/year in 2023, contributing a total of 2.38$\times$ 10^{10} m^3 biogas.

The cumulative biogas production potential demonstrates a significant increase over the decade, reflecting the growing integration of waste-to-energy technologies and enhanced feedstock availability. Cat-I contributes the largest share, followed by Cat-3, Cat-4, and Cat-2. The trend underscores the importance of scaling up biogas infrastructure and aligning policy incentives to support renewable energy generation. This growth trajectory highlights biogas as a critical component of sustainable energy strategies, with significant environmental and economic benefits. As biogas production increases, it helps mitigate the environmental impact of methane by converting it into usable energy.

Looking at the below graph, researcher can see that biogas production increases as the livestock population rises from 7.30 x 10^3 million m^3 in 2013 to 6.64 x 10^4 million m^3 in 2023, total manure estimated 3.05 x 10^5 million m^3 for category-I, 1.14 x 10^4 million m^3 for category-II, 1.10 x 10^5 million m^3 for category-III, 2.37 x 10^4 million m^3 for category-IV. This growing amount of biogas production presents a substantial opportunity for electricity generation, as more manure means more potential for generating biogas. Figure 5.2.

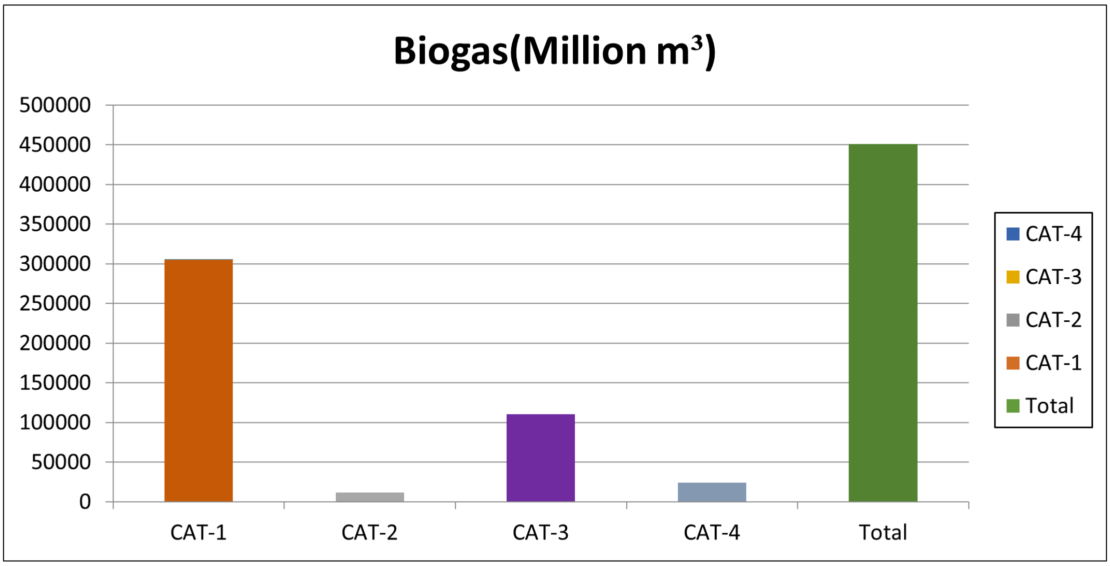


FIGURE 5.2: Biogas Production Potential for All categories

5.4 Electricity Generation

Electricity generation from biogas reduces the dependence on traditional fossil fuels (like coal and natural gas) for power generation. The steady increase in electricity production from biogas (from 15.13 TWh in 2013 to 87.88 TWh in 2023) highlights the growing role of biogas in the energy sector. The more electricity we generate from biogas, the less we rely on energy sources that emit CO_2.

The steady rise in electricity production aligns with the growing availability of biogas and reflects advancements in biogas to electricity conversion technologies.

Table 5.3: Electricity Generation Potential for All categories

Year	**CAT-I TWh/year**	**CAT-2 TWh/year**	**CAT-3 TWh/year**	**CAT-4 TWh/year**	**Total TWh/year**
2013	7.89	0.19	5.17	1.88	15.13
2014	9.54	0.20	5.50	2.06	17.30
2015	12.26	0.21	5.86	2.26	20.59
2016	15.28	0.24	6.25	2.47	24.24
2017	19.06	0.29	6.65	2.70	28.70
2018	23.77	0.36	7.09	2.96	34.17
2019	29.64	0.45	7.50	3.26	40.84
2020	36.97	0.61	8.04	3.58	49.21
2021	46.11	0.84	8.57	3.94	59.45
2022	57.52	1.16	9.12	4.35	72.15
2023	71.74	1.63	9.72	4.79	87.88
Total	329.76	6.18	79.47	34.25	449.66

The table showcases the electricity generation potential from biogas for the years 2013 to 2023, categorized into four groups (Cat-I, Cat-2, Cat-3, and Cat-4) measured in megawatt-hours (MWh) per year.

The data reflects consistent growth in electricity production across all categories, attributed to the increasing utilization of biogas as a renewable energy source. Cat-I displays the highest electricity generation potential, starting at 7.89×10^6MWh/year in 2013 and rising to 7.17×10^{10}MWh/year in 2023, contributing a cumulative total of 3.30×10^8 MWh over the decade. Cat-II records a steady increase from 1.90×10^5 MWh/year in 2013 to 1.63×10^6MWh/year in 2023, with a cumulative total of 6.18×10^6MWh. Cat-III begins at 5.17×10^6MWh/year in 2013 and grows to 9.72×10^6MWh/year by 2023, achieving a total of 7.95×10^7 MWh. Cat-IV progresses from 1.88×10^6 MWh/year in 2013 to 4.79×10^6MWh/year in 2023, contributing 3.42×10^7 MWh over the decade.

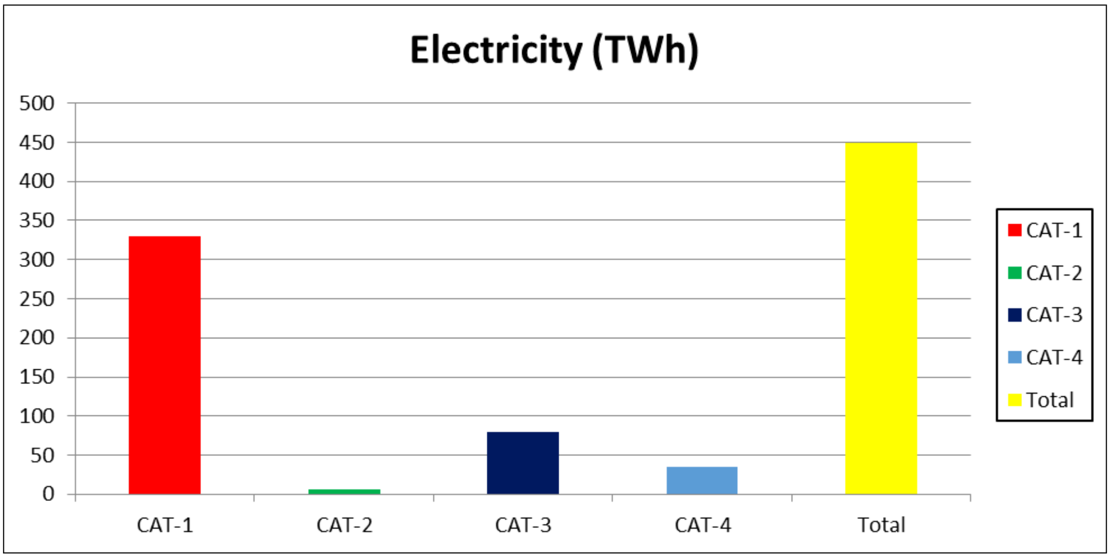


FIGURE 5.3: Electricity Generation Potential for All categories

The cumulative electricity generation potential highlights significant growth, with Cat-I contributing the largest share, followed by Cat-3, Cat-4, and Cat-2. The increasing trend in biogas-based electricity generation underscores its pivotal role in transitioning towards renewable energy solutions. This data emphasizes the need for scaling up biogas electricity infrastructure to meet sustainable energy demands while reducing dependency on fossil fuels.

5.5 Bio-fertilizer Production

Bio-fertilizer production is another important benefit of biogas systems. The byproducts of biogas production can be used as bio-fertilizer, a sustainable alternative to chemical fertilizers. The increasing production of bio-fertilizer (from 8.00 million tons in 2013 to 36 million tons in 2023) indicates that the byproducts of biogas production are being put to use in agriculture, enriching the soil without the harmful environmental impact associated with synthetic fertilizers.

TABLE 5.4: Bio-Fertilizer Potential for All categories

Year	**CAT-I M.Tons/year**	**CAT-2 M.Tons/year**	**CAT-3 M.Tons/year**	**CAT-4 M.Tons/year**	**Total Tons/year**
2013	2.63	0.25	4.52	0.60	8.00

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Table 5.4 continued from previous page

Year	CAT-I M.Tons/year	CAT-2 M.Tons/year	CAT-3 M.Tons/year	CAT-4 M.Tons/year	Total Tons/year
2014	3.18	0.26	4.81	0.65	8.91
2015	4.08	0.29	5.13	0.72	10.22
2016	5.09	0.32	5.46	0.79	11.66
2017	6.35	0.38	5.82	0.86	13.41
2018	7.92	0.48	6.20	0.94	15.54
2019	9.87	0.60	6.56	1.04	18.07
2020	12.32	0.82	7.03	1.14	21.31
2021	15.36	1.12	7.49	1.25	25.22
2022	19.16	1.55	7.98	1.38	30.07
2023	23.90	2.17	8.50	1.52	36.10
Total	109.87	8.24	64.98	10.89	193.98

The bio-fertilizer production potential has shown a consistent upward trend across Cat-I, Cat-II, Cat-III, and Cat-IV from 2013 to 2023, indicating a significant increase in organic waste utilization. Cat-I recorded the highest cumulative production of 1.10 × 10^8 tons/year, followed by Cat-III (6.95 × 10^7 tons/year), Cat-IV (1.09 × 10^7tons/year), and Cat-II (8.24 × 10^6 tons/year).

In 2013, production was relatively low, with Cat-I at 2.63 × 10^6 tons/year and Cat-IV at 5.99 x 105 tons/year. By 2023, this increased to 2.39 × 10^7 tons/year for Cat-I and 1.52 × 10^6 tons/year for Cat-IV, showing an approximately tenfold rise in CAT-I production.

The growth rate was particularly significant after 2017, aligning with advancements in biogas technology and organic waste recycling.

This increasing trend highlights the growing role of bio-fertilizers in sustainable agriculture, offering a renewable and eco-friendly alternative to chemical fertilizers.

sThe data suggests that enhanced waste management strategies and biogas expansion have directly contributed to higher bio-fertilizer yields, reinforcing its importance in improving soil fertility and reducing environmental pollution.

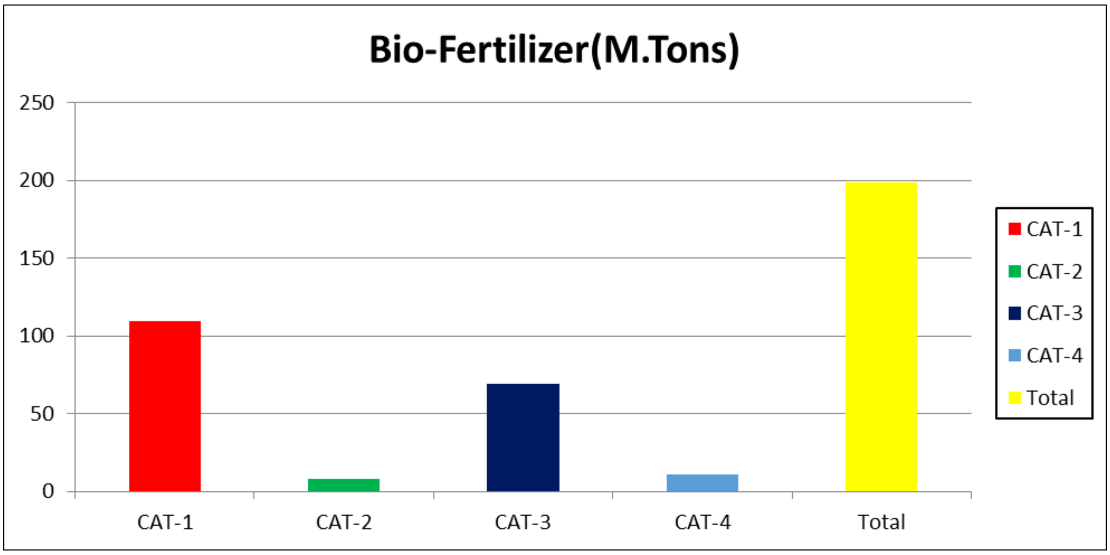

FIGURE 5.4: Bio-Fertilizer Potential for All categories

Looking at the above graph, researcher can see that manure production increases as the livestock population rises from 2.63 million tons in 2013 to 23.90 million tons in 2023, total manure estimated 109.87 million tons for category-I, 8.24 million tons for category-II, 64.98 million tons for category-III, 10.89 million tons for category-IV. This growing amount of manure presents a substantial opportunity for biogas production, as more manure means more potential for generating biogas.

5.6 GHG Emissions from Biogas Production (2013 – 2023)

The table shows GHG emissions in tons of CO_2, which represent the environmental impact of methane and other gases released from manure if left untreated.

TABLE 5.5: GHG Emission from Biogas for All categories

Year	CAT-I M.Tons CO_2/year	CAT-2 M.Tons CO_2/year	CAT-3 M.Tons CO_2/year	CAT-4 M.Tons CO_2/year	Total M.Tons CO_2/year
2013	14.26	0.69	14.02	2.56	31.53
2014	17.26	0.72	14.94	2.79	35.71

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Table 5.5 continued from previous page

Year	CAT-I M.Tons CO_2/year	CAT-2 M.Tons CO_2/year	CAT-3 M.Tons CO_2/year	CAT-4 M.Tons CO_2/year	Total M.Tons CO_2/year
2015	22.17	0.78	15.91	3.07	41.92
2016	27.64	0.88	16.95	3.35	48.82
2017	34.47	1.04	18.05	3.67	57.23
2018	42.99	1.29	19.23	4.02	67.54
2019	53.61	1.63	20.35	4.42	80.01
2020	66.87	2.22	21.82	4.86	95.78
2021	83.40	3.03	23.24	5.34	115.01
2022	104.04	4.20	24.75	5.89	138.89
2023	129.77	5.90	26.37	6.50	168.53
Total	596.50	22.37	215.62	46.47	880.96

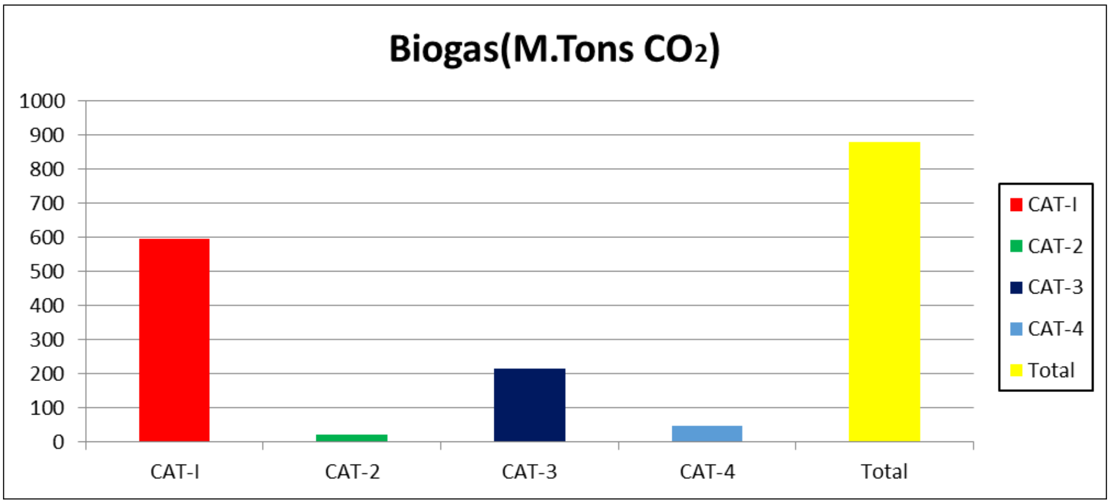

FIGURE 5.5: GHG Emission from Biogas for All categories

The greenhouse gas (GHG) emissions generated from biogas production has shown a consistent upward trend across all four categories (CAT-I, CAT-II, CAT-III, and CAT-IV) over the last decade. Among these, CAT-I recorded the highest cumulative emissions, reaching 597 million tons CO_2/year. This was followed by CAT-III with 216 million tons CO_2/year, CAT-IV with 46.5 million tons CO_2/year, and CAT-II with 223 million tons CO_2/year.

In 2013, emissions from CAT-I were 14.26 million tons CO_2/year. By 2023, this figure had escalated to 129.7 million tons CO_2/year, representing an almost nine fold increase over the decade. Similar trends were observed in CAT-III and CAT-IV, both of which experienced substantial growth in emissions. This escalation corresponds with the expansion of biogas production capacity, improved feedstock utilization, and advancements in anaerobic digestion technology. Notably, the sharpest annual increases were recorded after 2017, highlighting the intensification of biogas-related activities.

Despite being a renewable energy source, biogas production contributes to GHG emissions, particularly methane and CO_2. Effective mitigation measures, such as carbon capture technologies, optimized biogas plant efficiency, and sustainable waste management practices, are essential to minimizing environmental impact. Additionally, strategies like methane recovery systems, emission offset programs, and integration with carbon-neutral energy solutions can help balance the carbon footprint associated with large-scale biogas utilization. The increasing emissions indicate the urgent need for sustainable policies and innovations to ensure that biogas remains an environmentally viable alternative to fossil fuels.

5.7 GHG Emissions from Petrol (2013 – 2023)

The greenhouse gas (GHG) emissions from petrol combustion are significantly higher than those from biogas, despite being used in the same quantity for energy production.

Table 5.6: GHG Emission from Petrol for All categories

Year	**CAT-I M.Tons CO_2/year**	**CAT-2 M.Tons CO_2/year**	**CAT-3 M.Tons CO_2/year**	**CAT-4 Tons CO_2/year**	**Total M.Tons CO_2**
2013	37.28	1.80	36.65	6.68	82.41
2014	45.12	1.87	39.04	7.29	93.32
2015	57.95	2.03	41.58	8.01	109.57
2016	72.24	2.30	44.29	8.76	127.59
2017	90.09	2.73	47.17	9.59	149.58
2018	112.37	3.38	50.25	10.51	176.51

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Table 5.6 continued from previous page

Year	CAT-I M.Tons CO_2/year	CAT-2 M.Tons CO_2/year	CAT-3 M.Tons CO_2/year	CAT-4 Tons CO_2/year	Total M.Tons CO_2
2019	140.13	4.26	53.18	11.54	209.11
2020	174.78	5.81	57.02	12.71	250.32
2021	217.99	7.92	60.74	13.96	300.61
2022	271.92	10.98	64.70	15.41	363.01
2023	339.17	15.41	68.92	16.98	440.49
Total	1559.04	58.48	563.54	121.44	2302.51

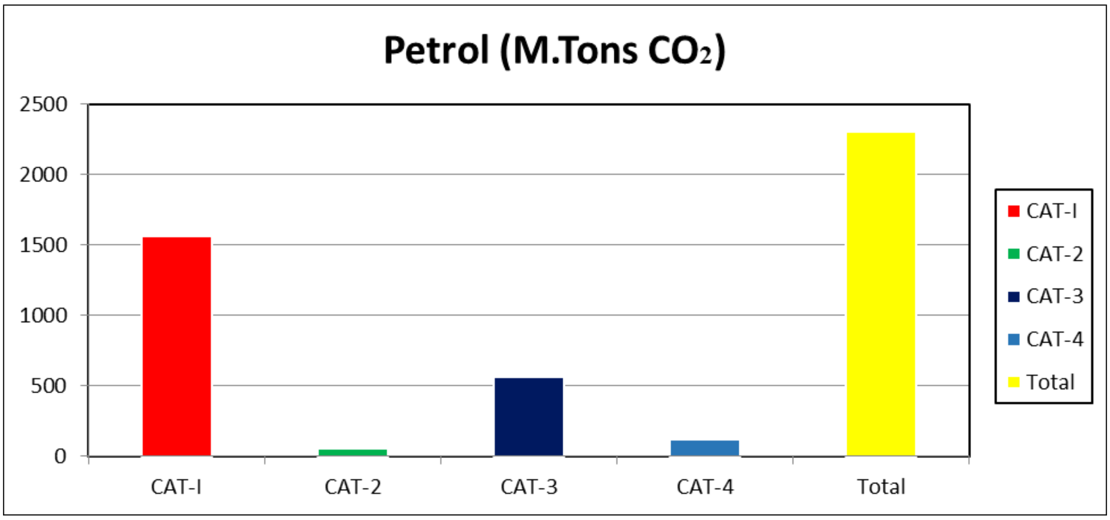

FIGURE 5.6: GHG Emission from Petrol for All categories

The greenhouse gas (GHG) emissions from petrol consumption have shown a consistent increase across all categories (CAT-I to CAT-IV) over the past decade. The highest emissions were recorded in CAT-I, totaling 1559.04 million tons CO_2, followed by CAT-III (563.54 million tons CO_2), CAT-IV (121.44 million tons CO_2), and CAT-II (58.48 million tons CO_2).

In 2013, CAT-I emitted 37.28 million tons CO_2, which surged to 339.17 million tons CO_2 in 2023, reflecting a nearly tenfold increase. A similar pattern was observed in other categories, with a sharp rise post-2017 due to increased fuel consumption and economic growth.

Compared to biogas, which emits only 0.88 kg CO_2 per liter, petrol releases 2.3 kg CO_2 per liter, making it 2.6 times more polluting. The transition to cleaner alternatives, such as biogas and renewable energy sources, is crucial to reducing carbon emissions and mitigating climate change.

5.7.1 GHG Emission Reduction

GHG emission reduction is calculated by comparing the GHG emissions from the baseline (petrol) to the reductions achieved through biogas production.

By 2023, 492,000 tons of CO_2 are being reduced annually contribute to biogas production, as it replaces the need for energy generated from fossil fuels (like petrol).

Petrol is a fossil fuel that, when burned, releases carbon dioxide (CO_2) and other greenhouse gases into the atmosphere, contributing to climate change.

Biogas, on the other hand, is a renewable energy source that, when used instead of petrol, results in lower GHG emissions.

Table 5.7: GHG Emission Reduction for All categories (Million Tons)

Year	**GHG Emission (Petrol)**	**GHG Emission (Biogas)**	**GHG Emission Reduction**
2013	82.41	31.53	50.88
2014	93.32	35.71	57.62
2015	109.57	41.92	67.64
2016	127.59	48.82	78.77
2017	149.58	57.23	92.35
2018	176.51	67.54	108.98
2019	209.11	80.01	129.10
2020	250.32	95.78	154.55
2021	300.61	115.01	185.59
2022	363.01	138.89	224.12
2023	440.49	168.53	271.95
Total	2302.51	880.96	1421.55

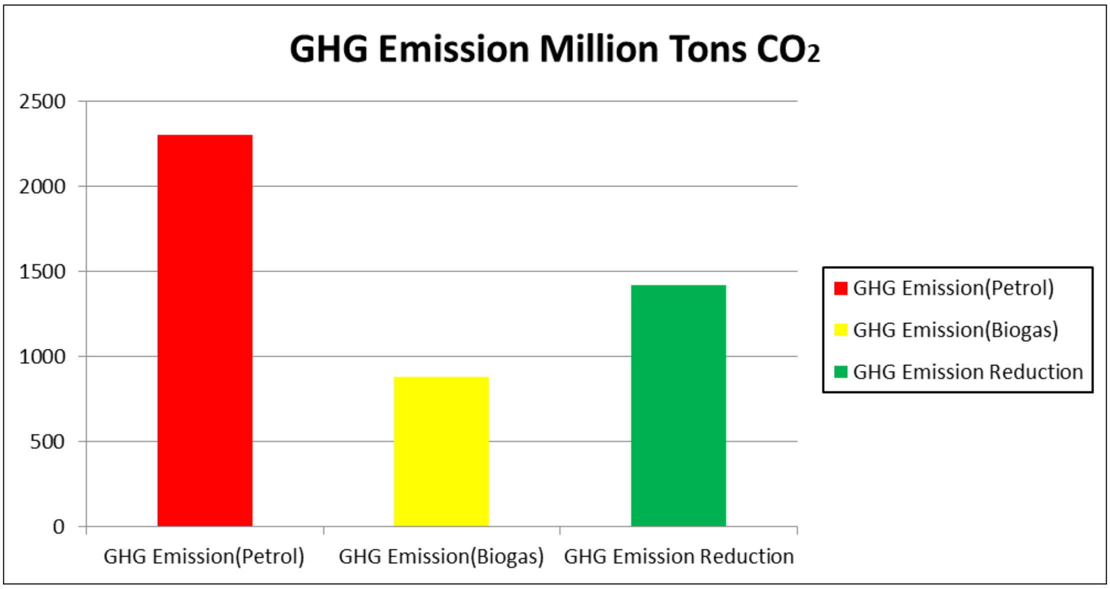

FIGURE 5.7: GHG Emission Reduction for All categories

Petrol is a fossil fuel, and its combustion for energy production releases substantial amounts of CO_2 into the atmosphere. Biogas, by contrast, is a renewable resource that produces far fewer emissions when used for energy generation. The GHG reduction figures show that biogas has a much lower net carbon footprint than petrol. In 2023, 271.95 million tons of CO_2 are being prevented from entering the atmosphere thanks to the increased use of biogas. By using biogas instead of petrol, the researcher can reduce the carbon footprint an estimated amount of 1421.55 CO_2 million tons from 2013 to 2023 positively.

5.8 Economic Viability of Biogas and Solar System

The comparative analysis of the biogas plant and solar PV system, both priced at Rs. 1,200,000, reveals distinct operational and economic characteristics. The biogas system demonstrates superior energy economics, producing 45 kWh daily at just Rs. 4 per unit, significantly outperforming the solar system's 12 kWh at Rs. 14.5 per unit. Beyond electricity generation, the biogas plant yields valuable bio-fertilizer (40 kg/day worth Rs. 600 daily), adding substantial secondary income that solar cannot match. This makes biogas particularly advantageous in agricultural settings where organic feedstock is readily available. The solar system, while offering cleaner energy with minimal maintenance, proves less cost-effective in terms of pure energy output and lacks additional revenue streams.

From a sustainability perspective, both systems contribute to emissions reduction, but their optimal applications differ markedly. The biogas solution excels in rural, waste-rich environments where its dual output of energy and fertilizer creates a circular economy model. Solar technology, despite higher per-unit costs, remains indispensable for urban and off-grid applications where space and organic materials are limited. The choice between systems ultimately depends on local conditions - biogas offers greater economic returns where implementable, while solar provides essential flexibility for diverse locations. This comparison underscores the importance of context-specific renewable energy solutions, with biogas representing the more economically compelling option when supported by adequate biomass resources.

Chapter 6

Conclusion and Recommendations

This is the final section of the research work that involves a description of research outcomes and conclusions. Thorough insight related to the current research work and recommendation for future work is outlined. Moreover, theoretical calculation of all four categories provides the potential of biogas, electricity, bio-fertilizer, GHG emission and reduction of GHG emission by using biogas instead of petrol. Also some suggestions are requested.

6.1 Conclusion

This study demonstrates the immense potential of manure utilization for renewable energy generation, environmental sustainability, and resource optimization. Across four categories of animals, manure was effectively converted into biogas, electricity, and bio-fertilizer, significantly reducing greenhouse gas (GHG) emissions over the analyzed 11-year period (2013–2023). The following concluded as under:-

- The final concluded on the fiscal year 2023 that livestock waste amounted, biogas production, electricity generation, bio-fertilizer and GHG emission reduction to 573.24 million tons, 8.63×10^4 million m^3, 87.88 TWh, 36.10 million tons and 271.95 million tons of CO_2 respectively.

- The prediction/forecasting concluded on the year 2030 that livestock waste amounted, biogas production, electricity generation, bio-fertilizer and GHG emission reduction to 1810 million tons, 2.82×10^5 million m^3, 286 TWh, 113.91million tons and 891.1 million tons of CO_2 respectively.

- The developed biogas potential calculator successfully integrates actual calculation for manure, biogas, electricity, bio-fertilizer output, and GHG emissions.

- The 12 kWh solar system also costs Rs 120,000 but generates power at Rs 13.6/unit without by-products. Both have a 20 - 25 year lifespan. The 50 m^3 biogas system costs Rs 120,000, produces energy at Rs 4/unit, and yields 40 kg/day of bio-fertilizer (Rs 600/day savings).

6.2 Recommendations

Based on the study's findings, the following recommendations are recommended to improve the use of manure for renewable energy generation and environmental sustainability. Because the technology has enormous benefits, efforts should be increased to ensure that more homes use it. The full potential of biogas can only be realized by significantly increasing the number of biogas plants. To achieve this, efforts should focus on capacity-building initiatives for farmers, fostering collaboration among farmers, biogas manufacturers, artisans, researchers, NGOs, donors, financial institutions, and policymakers.

- The Government of Pakistan should assist farmers by offering incentives, such as subsidies for biogas construction materials or access to credit. These initiatives would enhance affordability and promote the widespread adoption of biogas technology.

- It is recommended that efforts be focused on capacity building programs for farmers, strengthening linkages between farmers, biogas fabricators and artisans, researchers, NGOs, donors, creditors and policy makers.
- The policymakers, investors, and energy managers should use the developed forecasting model/calculator to assess the biogas plant capacities and the viability of biogas plant as a renewable energy resource.
- The Government of Pakistan should support to farmers by giving incentives such as subsidies to biogas construction materials
- Since the adoption of biogas technology involves complex interactions between users and socio-economic factors, it is crucial to understand these connections from regions where it has been successfully implemented. Creating similar conditions in areas with low adoption can help promote its use. Organizing exchange visits for non-adopter farmers to biogas plants operated by adopters is recommended to facilitate knowledge transfer and encourage wider adoption.
- Enhancing the overall well-being of households can significantly increase biogas adoption rates. Wealthier households, those with highly educated heads, and those with larger cattle herds are more likely to adopt the technology. Therefore, implementing programs that improve household finances and resources is recommended to encourage the widespread use of biogas technology.
- Develop strategies to compress and package biogas into tradable units. In addition, ways for converting the gas into electrical energy for illumination and mechanical operation should be investigated. This can earn consumers extra revenue while avoiding surplus gas wastage.
- Poultry farming integration benefits biogas users significantly. When poultry manure is used to produce gas, the quantities of CH4 in the gas increase, as does the calorific value of the fuel. Farmers are urged to supplement their cow feed with chicken dropping, particularly because it is locally available and does not cost anything extra. This will help to increase methane content

while decreasing CO_2 percentage. Most farmers benefit because they have integrated poultry into their operations.

- Governments and policymakers should introduce supportive policies and financial incentives, including subsidies, tax benefits, and grants, to promote the adoption of biogas and bio-fertilizer technologies.
- Investment in infrastructure, including biogas plants, manure collection systems, and electricity generation facilities, is essential to scale up manure utilization and improve efficiency.
- Continued research is needed to develop advanced technologies that maximize biogas yield, enhance bio-fertilizer quality, and improve overall system efficiency while reducing costs.
- Programs to educate farmers, industry stakeholders, and the general public about the economic and environmental benefits of manure utilization should be prioritized. Training sessions and technical assistance can help improve adoption rates.
- Encourage the use of bio-fertilizer as a sustainable alternative to chemical fertilizers in agriculture to promote soil health, reduce dependency on synthetic inputs, and create a circular economy.
- Foster partnerships between governments, private sectors, and research institutions to enhance resource sharing, innovation, and large-scale implementation of manure-based renewable energy projects.
- Establish robust systems to monitor the performance of biogas plants, measure GHG reductions, and evaluate the socio-economic impact of manure utilization projects to ensure continuous improvement.

6.3 Areas for Further Research

- Additional research is necessary to measure the precise reduction in methane emissions achieved through biogas utilization. This information is crucial for allowing farmers to engage in carbon credit trading, offering them an extra revenue stream. To facilitate this, baseline data on methane (CH_4) emissions from untreated cow dung prior to biogas system installation must be gathered. Carbon credits are determined based on baseline emission levels rather than the volume of methane captured and combusted. Investigating the potential for carbon financing of biogas projects under the Clean Development Mechanism could act as a strong incentive to promote adoption, especially in rural regions with substantial untapped potential.

- Further research is needed to determine the impact of bio-digester temperature, pressure, and retention duration, as well as cattle feed regimes, on methane production. This was a major gap in the current study and a significant weakness in the research. Farmers' setup was employed, and the study had no control over the digesting process at all. The digesters differed in little features such as the length and diameter of gas pipes and valves, the volume of digestate, and the frequency of feeding. There is a need to explore these factors and feed regimes in a more controlled manner to see if there is any variation in gas yield based on farmer practice. Feed management, harvest stage, and cow feeding intensity should all be determined.

- To improve biogas quality, research should focus on removing CO_2 and compressing the gas into high-pressure cylinders or storage devices for trade. Currently, farmers who produce more than they need lack systems for bottling and storing the gas. As a result, there is a need to investigate ways for cleansing carbon dioxide gas, as well as how to store and package in units that may be sold in rural areas.

- Further research is needed to develop methods for enhancing biogas quality by increasing methane content to 90%. This improvement would make biogas suitable for use in powering machinery and automobiles.

- Research is needed to determine the cost-effectiveness of integrating cows with other animals, as well as the impact of various feeds on milk production, which is the primary goal of dairy farming.

- Hydrogen sulfide (H_2S) is a major pollutant with highly toxic and corrosive properties, making its presence in biogas highly undesirable. The highest methane-yielding feed combinations also produced elevated H_2S levels, highlighting the need for effective desulfurization methods before the gas reaches end users, such as household kitchens.

- Finally, study is needed to quantify the nutrients in bio-slurry and their impact on soil fertility and food production.

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